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WEATHER EFFECTS ON APPROACH AND LANDING SYSTEMS

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FINAL REPORT

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1. INTRODUCTION

The current standard instrument landing system (ILS) uses frequencies in the 108 to 335 MHz band. Requirements for more precise guidance systems to meet the projected needs of aviation have produced interest in higher radio frequencies, such as 10 and 15 GHz. Although these frequencies offer many advantages in instrumentation, they are also affected to a greater degree by certain weather conditions, in particular, heavy rain. Because high reliability under all conditions is necessary, the influence of weather on system reliability is an important factor in selecting frequencies for future guidance systems. The two most important weather factors influencing 10 and 15 GHz propagation are precipitation attenuation and atmospheric refraction (bending). Other phenomena, such as turbulence and wind shear, also need to be considered, but they are probably more important to operational or control procedures than to system design.

2. PRECIPITATION ATTENUATION

The attenuation of microwave energy by precipitation is a result of absorption of energy by the water volume and the scattering of energy by the drops; it is affected by temperature, drop size and shape, terminal velocity of the drops, total water volume, as well as the frequency used. The early theoretical approach of Ryde and Ryde (1945) has been generally accepted and has been somewhat refined in recent years by Medhurst (1965).

According to the Ryde and Ryde theory, maximum and minimum rainfall attenuations occur when precipitation over the entire radio path is composed of drops that are all the same size. These theoretical values should represent the outer limits of attenuation since rainfall

is normally composed of drops of many different sizes. At frequencies from 5 to 15 GHz, the maximum attenuation occurs with considerably larger drops than the minimum. Maximum and minimum values given by Medhurst (1965) are:

Attenuation in dB/ km/ mm/ hr

	5 GHz	7.5 GHz	10 GHz	15 GHz
Maximum	0.053	0.058	0.068	0.095
Minimum	0.0009	0.0027	0.006	0.017

(e.g., at 15 GHz, rate 100 mm/hr, attenuation/km is 9.5 dB maximum and 1.7 dB minimum).

A major difficulty in relating rainfall rates directly to microwave attenuation is the variability in the raindrop size distribution with changes in rain intensity. Although many measurements of drop-size distributions have been made, considerable uncertainty still exists in the choice of drop size for rain attenuation estimates.

In natural rainfall even a relatively small volume contains drops of several different sizes. Extensive measurements made by Laws and Parsons (1943), at rainfall rates varying from 0.01 to 6.0 in/hr (0.25 to 152 mm/hr), showed a wide range of drop sizes at any particular rainfall rate. At a 6 in/hr rate, their data showed a drop size variation from 0.25 mm diameter to 7.0 mm diameter, with the distribution peak at 3.00 to 3.25 mm diameter. Figure 1 shows the tendency for more of the larger sized drops at the higher rain rates.

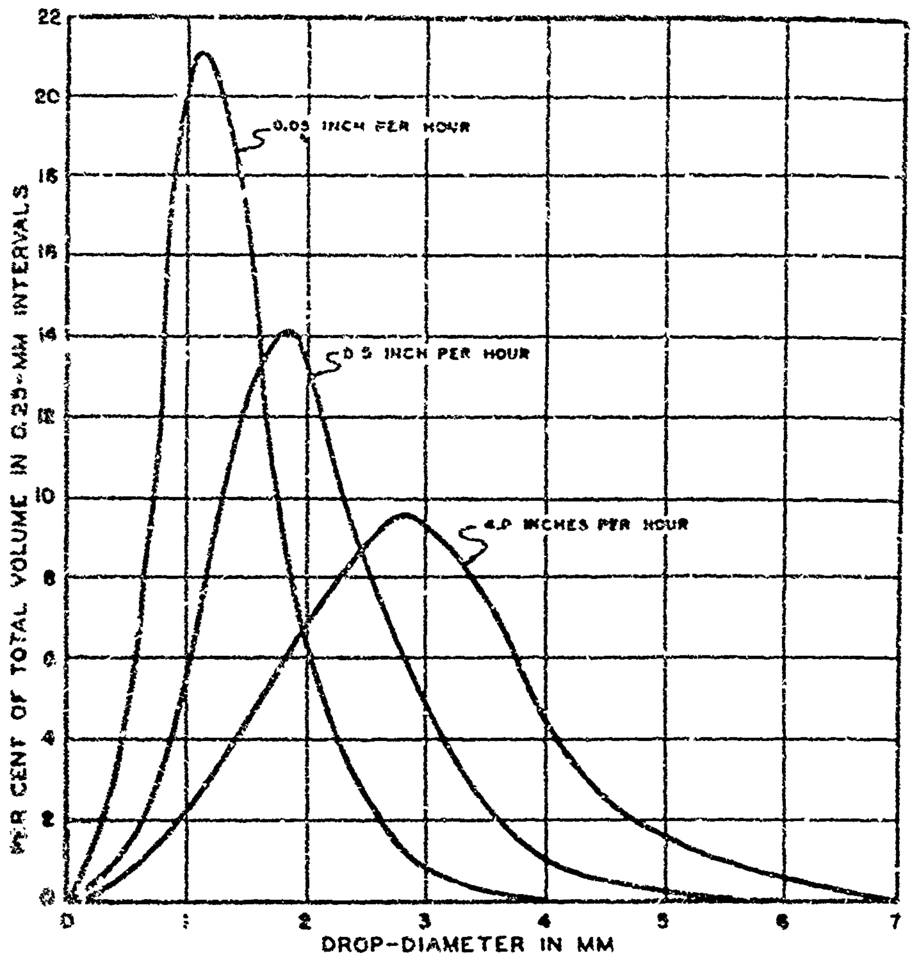

Figure 1. Percent of total volume contributed by drops of various sizes for three rainfall-rates, as computed for 0.25-mm intervals of diameter (Laws and Parsons, 1943).

The theoretical estimate of precipitation attenuation, assuming the Laws and Parsons drop-size distribution, rather than the uniform distribution used for the "maximum-minimum" calculations, is shown in figure 2. These curves are based upon Medhurst's extension of the work of Ryde and Ryde. Table 1 is based upon the same values as figure 2 and shows the effect of rain attenuation for a system with 40 dB margin:

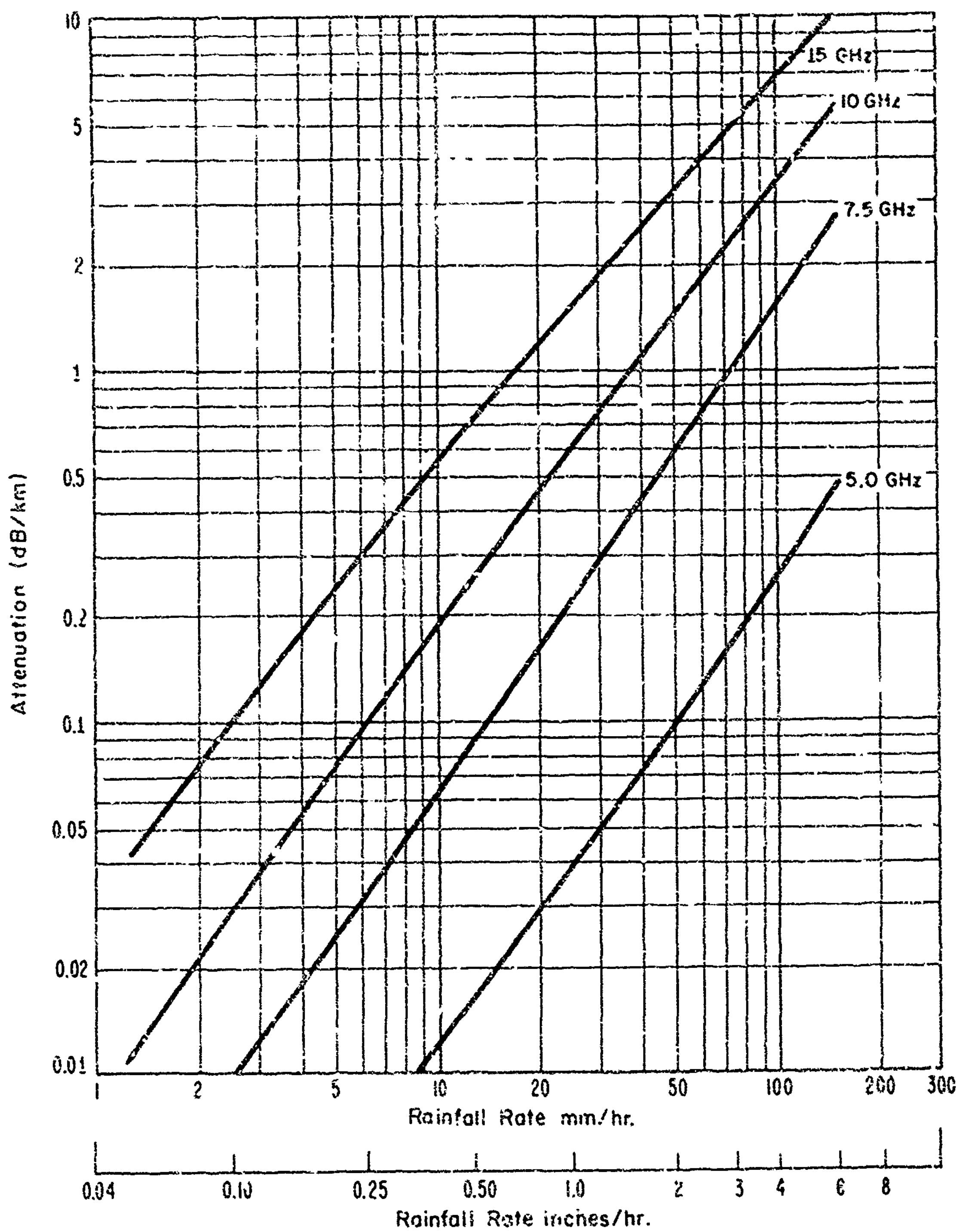

Figure 2. Theoretical attenuation based on the Laws and Parsons drop-size distribution (after Medhurst, 1965).

Table 1. Distance Over Which Uniform Rain Must Extend Along a Radio Path to Cause 40 dB Attenuation

Rainfall Rate		Distance in km for			
mm/hr	in/hr	5 GHz	7.5 GHz	10 GHz	15 GHz
25	0.98	1053	182	66.8	26.2
50	1.97	413	69	27.6	12.2
100	3.94	154	25.8	11.7	5.9
150	5.91	85	14.8	7.3	3.9

At 5 GHz, rain attenuation is less than 1 dB/km, even for extreme rain rates, so it is generally not a limiting factor in system design. At 7.5 GHz, rain attenuation at the heavier rates needs to be considered in system design if very high reliability is desired (e.g., see Kirby and Samson, 1969). At 10 and 15 GHz, additional system margin would be necessary to insure a 20 mile (32 km) range in areas with significant shower-type rainfall.

The measured attenuation data available have in most cases been taken without adequate precipitation measurements. There are great instrumentation difficulties in measuring instantaneous drop-size distribution over a path of practical length. A random distribution is usually assumed, and the attenuation correlated directly with rainfall rate, as measured at points on or near the path. Determining the path average rainfall rate from point measurements along the path is probably the main source of error in the experimental measurement of rainfall attenuation. If a short path is used with close gage spacings, the signal attenuation must be measured very precisely; however, if the path length is increased to improve the accuracy of the attenuation measurement,

the cost of providing a dense rain gage network usually becomes prohibitive. The assumption that is sometimes made when gages are spaced several km apart--namely, that precipitation is uniform over the interval extending halfway to the adjacent gages--is not consistent with what is known about rain variability, especially under thunderstorm conditions. Even when gage spacings are reduced to a few hundred meters the path rainfall is not being measured, it is being sampled, and the sampling errors can be very large. In the U. S. the average gage density is one per 230 sq. miles, but this is not uniform throughout the country. The Hydrometeorological Section of the Weather Bureau (1947) compared the effects of different gage spacings on apparent storm intensity by selecting certain gage patterns in a densely instrumented drainage basin in Ohio. In one storm, a gage density of one per 375 sq. miles indicated an areal rainfall maximum of 0.62 in, but when the complete network of 449 gages was considered (one gage per 18 sq. miles) several centers of more intense rainfall were apparent, including one with a total of 3.51 in and another with 5.36 in.

Table 2 summarizes the results of attenuation measurements made in several different countries at frequencies ranging from 9.4 to 15.3 GHz. Most of the data show a tendency for measured attenuation to be somewhat higher than the theoretical values based on the Laws and Parsons drop-size distribution, but lower than the theoretical maximum based on uniform drop size. At very low rain rates, however, several investigators have found attenuation much greater than predicted (e.g., Blevis et al., 1967; Bailey and Straiton, 1969; Skerjanec and Samson, 1970).

Figures 3 through 6 compare some measured data at 10 to 15 GHz with the theoretical estimates.

The attenuation by snow is usually not a limiting design consideration when the snow is "dry" (i.e., when temperatures are well below freezing), but when the temperature is near $0^{\circ}C$ and the snow is "wet" or mixed with rain or sleet the microwave attenuation may be several times what would be expected with warm rain at the same rate of fall. The liquid "water equivalent" of snow (or the amount of water obtained if snow is melted) is usually relatively small compared with rainfall from a summer thundershower, and it varies over a wide range. Wilson (1955) gave extremes of 3 to 30 percent of water equivalent for newly fallen snow, and an overall mean value of 8 to 9 percent. If we assume a value of 10 percent, a 5 in/hr snowfall would have a water equivalent of 0.5 in/hr (12.7 mm/hr). A rainfall of this intensity would attenuate 15 GHz signals about 0.7 dB/km; but, if we now assume that it is wet snow, which gives four times more attenuation than a rain equal to the water equivalent (as suggested by the measurements of Takada and Nakamura, 1966), the attenuation would be 2.8 dB/km, or about what would be expected with rain at a rate of 1.73 in/hr (44 mm/hr).

Since horizontal and vertical visibility are usually greatly restricted by snowfall, any degradation of an approach system signal caused by snowfall would probably occur at a critical time, i.e., when demands on the system were high. Wet snowfall is more likely to occur in early fall and late spring than during midwinter (temperate climates).

3. SOME CHARACTERISTICS OF RAINSTORMS

A survey of the literature of storms and precipitation (Skerjanec and amson, 1970) indicated that rainfall is seldom uniform, even over small areas. Nearly all high rainfall rates occur in thunderstorms, which vary in size from 1 to 10 miles diameter (1.6 to 16 km) for single storms. A good average value is about 5 miles (8 km); however, very

Table 2. Summary of Measurements of Microwave Attenuation by Rainfall Between 9.4 GHz and 15.3 GHz

Reported By	Radio Freq., GHz	Path Length & Location	Period	Rain Gages	Results
Robertson & King, 1946	9.4	900 ft, Holmdel, New Jersey	2 storms; July 31, 1942, Aug. 10, 1942	Only one; 30-cm diameter funnel on roof of bldg. connected to graduate in room below; read at varying intervals by observer, mostly 1 min. Gage was 500-1000 ft from path.	Observed rain rates as high as 135 mm/hr; estimated attenuation for 100 mm/hr rain is 4 to 5 dB/mile. Suggest as a working relationship 0.05 dB/mile/mm/hr (0.031 dB/km/mm/hr). Medhurst (1965) indicates most of these observations fall between the Ryde and Ryde maximum and the Laws and Parsons' curve.
Hathaway & Evans, 1958	11	27.7 and 12.6 miles, southern Alabama	About 1 yr; 1956	Tipping-bucket type; tip at 0.01 inch; spacing 2.3 miles (3.7 km); separate recorder each gage.	Rainfall rate assumed to be uniform for 1 mile either side of a gage; attenuation for each 2-mile section obtained by the relationship: Attenuation (dB) = $2kR^{\alpha}$, where k = 1.395 dB/mi/in/hr and α = 1.3. Medhurst's analysis shows these data below the Ryde and Ryde maximum and in general agreement with the Laws and Parsons' curve, but with considerable scatter of points, he remarks that the assumption made would not usually be valid.
Takada & Nakamura, 1966	11.325	14.3 km, Japan	55 days in Dec., Jan., & Feb.	5 gages, 3.6 km apart; self-recording type, 1-min intervals.	Precipitation rates up to 50 mm/hr in rain and up to 30 mm/hr in mixed snow, sleet, and rain. Temperatures near 0°C. Attenuation for snow mixed with some sleet was about 6.5 times that for rain at 0°C, or about 4.1 times that for rain at 18°C (for equivalent liquid precipitation rates; i.e., snow was melted before measurement).
Forbes, 1968	12	U. S. A. (?)	Not given.	None	On basis of experience with a 12 GHz system, severe fog will cause about 1/4 dB/mile attenuation (visibility 100 ft or less).
Bell, 1967	11	55 km; southern England	1 year	None on path; rain data from Abingdon weather station, 8 miles SW of midpath.	Maximum hourly precipitation correlated with maximum path attenuation; these did not necessarily occur at same time as rain gage was off path. Signal faded below normal because of precipitation about 3 percent of time. During periods of rain and snow (mixed) attenuation was 6 to 8 times that for rain alone. At about 3 mm/hr, path attenuation of 3 to 4 dB observed; this compares to Medhurst's value of 2.75 dB, based on Laws and Parsons. (Maximum rainfall for case reported was less than 6 mm/hr (0.24 in).
Blevis, Dohoo, & McCormick, 1967	14.916	15.78 km; Ontario, Canada	May - Oct. incl., 1965	10-inch tipping bucket, 0.01 in/tip; 6 gages spaced 2 to 5 miles; data telemetered to receiving terminal for recording.	Observed rainfall rates up to about 40 mm/hr; no definite tendency for measured attenuation to be above maximum theoretical values as given by Medhurst, but in general the attenuation is greater than that obtained using the Laws and Parsons' distribution. At rates of less than 2 mm/hr the observed attenuation was appreciably greater than the predicted values. Path attenuation during snow exceeded 4 dB only twice in winter of 1956-66; on both occasions precipitation was rain and snow mixed.

Bailey & Stratton, 1969	16.3	12.5 mile (20 km), Austin, Texas	Dec. 1968-Feb. 1969 incl.	3 tipping-bucket, 0.01 in/tip; about 10-km spacing.	Only one case of moderately heavy rain; maximum path rate estimated to be about 0.54 in/hr (13.7 mm/hr). (This was a winter season rain associated with a stationary frontal zone and rain was probably more uniform than would be expected for summer thundershower conditions.) Observed attenuation is somewhat higher than the theoretical Medhurst-Laws and Parsons' values, with a tendency toward rather large differences at very low rainfall rates (less than 1 mm/hr).
Stracca, 1969	11	20 km & 9 km, Po Valley, Italy	May - Oct. 1967	9 balance-type, 1 mm/shift; 2.2 km spacing; data telemetered to 1 terminal and recorded simultaneously.	Individual gages indicated rates as high as 200 mm/hr for periods of few minutes; rates of 110 mm/hr (4.33 in/hr) or more were never observed simultaneously at both terminals of 20-km path. 88 percent of storms estimated to be 5 km or less in diameter. Most attenuation events lasted less than 20 min, but of 3 lasting more than 20 min two were associated with highest attenuation measured (40 dB); one of these lasted 40 min and the other 27 min (thus exceeding the permissable outage for a 99.99 percent reliability on a link with 40 dB margin). Heavy showers, in general, cover very small areas and the more intense the precipitation the smaller the area covered by the storm. Measured attenuation at 18 GHz about twice that at 11 GHz. Approximate attenuation coefficient at 11 GHz ranged from 0.02 dB/km/mm/hr to 0.09 dB/km/mm/hr, depending on rain intensity; these are slightly higher than the theoretical values given by Medhurst (who calculated 0.025 dB/km/mm/hr at 10 mm/hr rate and 0.04 dB/km/mm/hr at 100 mm/hr rate).
Skerjanec & Samson, 1970	10 & 14.43	4.67 km, northern Mississippi	Feb. - May incl., 1969	20 tipping-bucket, 0.01 in/tip; remoted by cable for simultaneous recording at one terminal; gage spacing approximately 800 ft (0.24 km).	10- and 14.43-GHz systems operated simultaneously; radio paths separated by less than 2 meters. Rain attenuation at 14.43 GHz approximately twice the attenuation at 10 GHz. Generally somewhat higher attenuation indicated than predicted from Medhurst's calculations using Laws and Parsons' distribution, but below the theoretical maximum--except that at 14.43 GHz there appeared to be a tendency for attenuation above the theoretical maximum when rainfall rates were less than about 25 mm/hr (1 in/hr). Path attenuation versus rainfall rate correlations were made only for periods when rain appeared to be uniform over the path. Highest path average rate 137 mm/hr (5.40 in/hr).
Turner, Easterbrook, & Golding, 1966	11.0 & 11.5	5 paths, 15 to 36 miles; southern England	1 year each path; not all same year.	Heated gage at terminals and midpath; type not specified.	Over the period of observation (about 3 yrs) neither precipitation nor intermodulation arising from multipath would have significantly restricted use of this band. Precipitation not a major cause of fading, either on annual or monthly basis. For each path, for months when fading was worst, precipitation fading usually negligible. Wet snow caused 20 dB fade for 4 hrs on one path with rat of no more than 3 mm/hr (15 mi path). Point rates of over 100 mm/hr observed; deepest rainfall fade was 32 dB, associated with point rate of 80 mm/hr (note that these are not "path-average" rates). Cold, dry snow had little effect on transmissions.

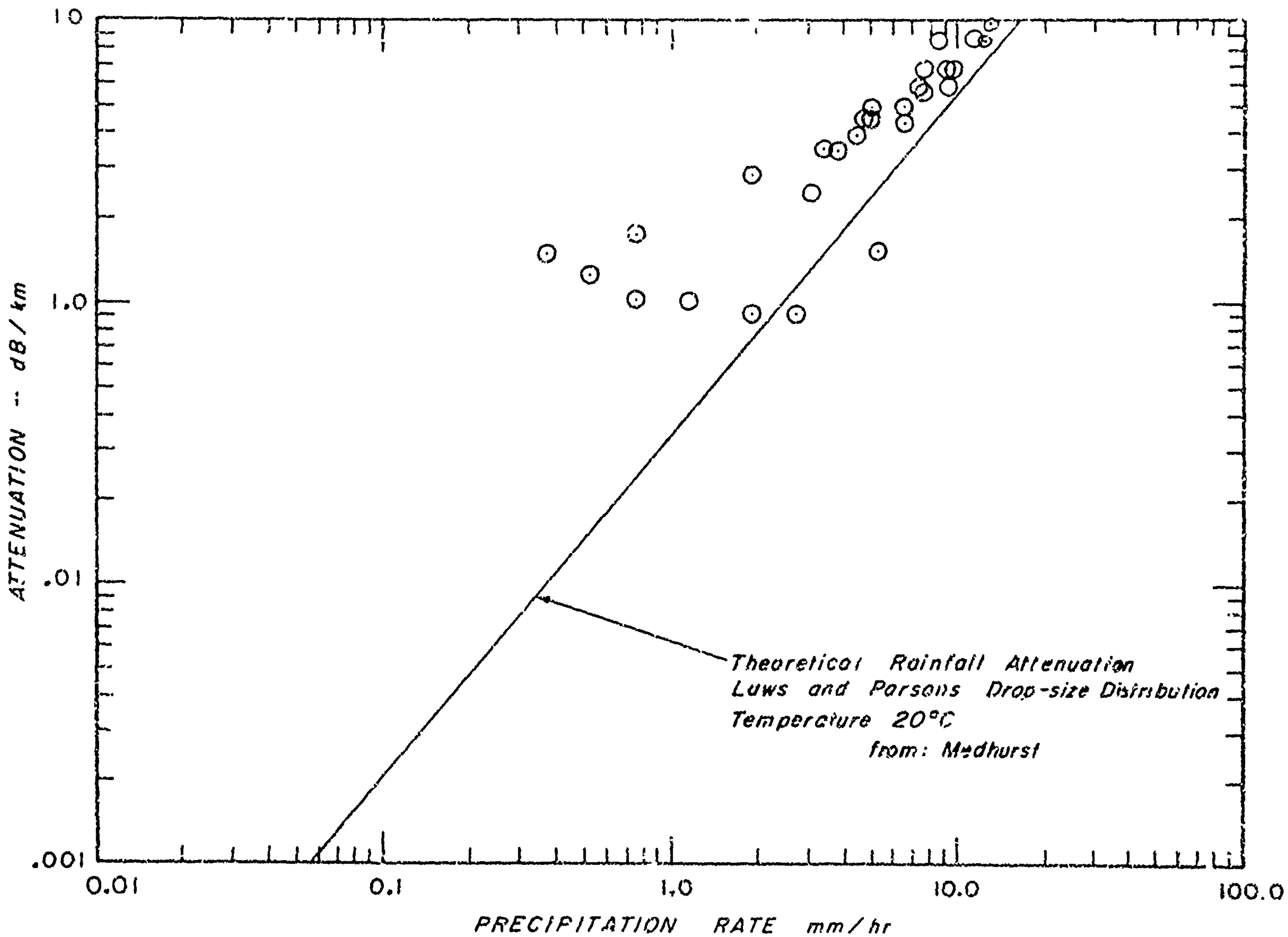

Figure 3. Measured rainfall attenuation at 15 3 GHz near Austin, Texas, on February 13, 1969 (Bailey and Straiton, 1969).

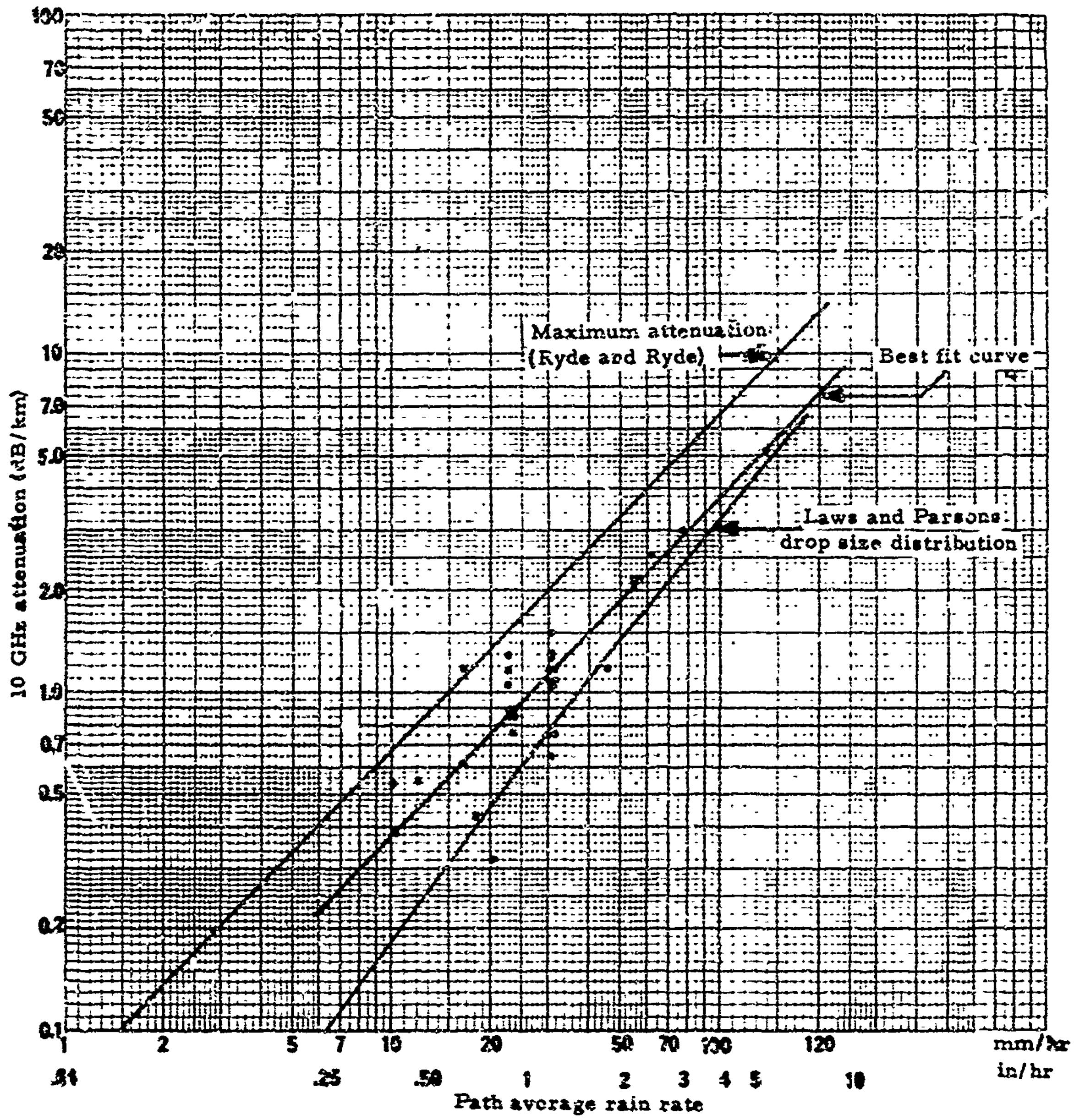

Figure 4. Measured rainfall attenuation at 10 GHz at Mississippi State Univ., February through May 1969 (Skerjanec and Samson, 1970).

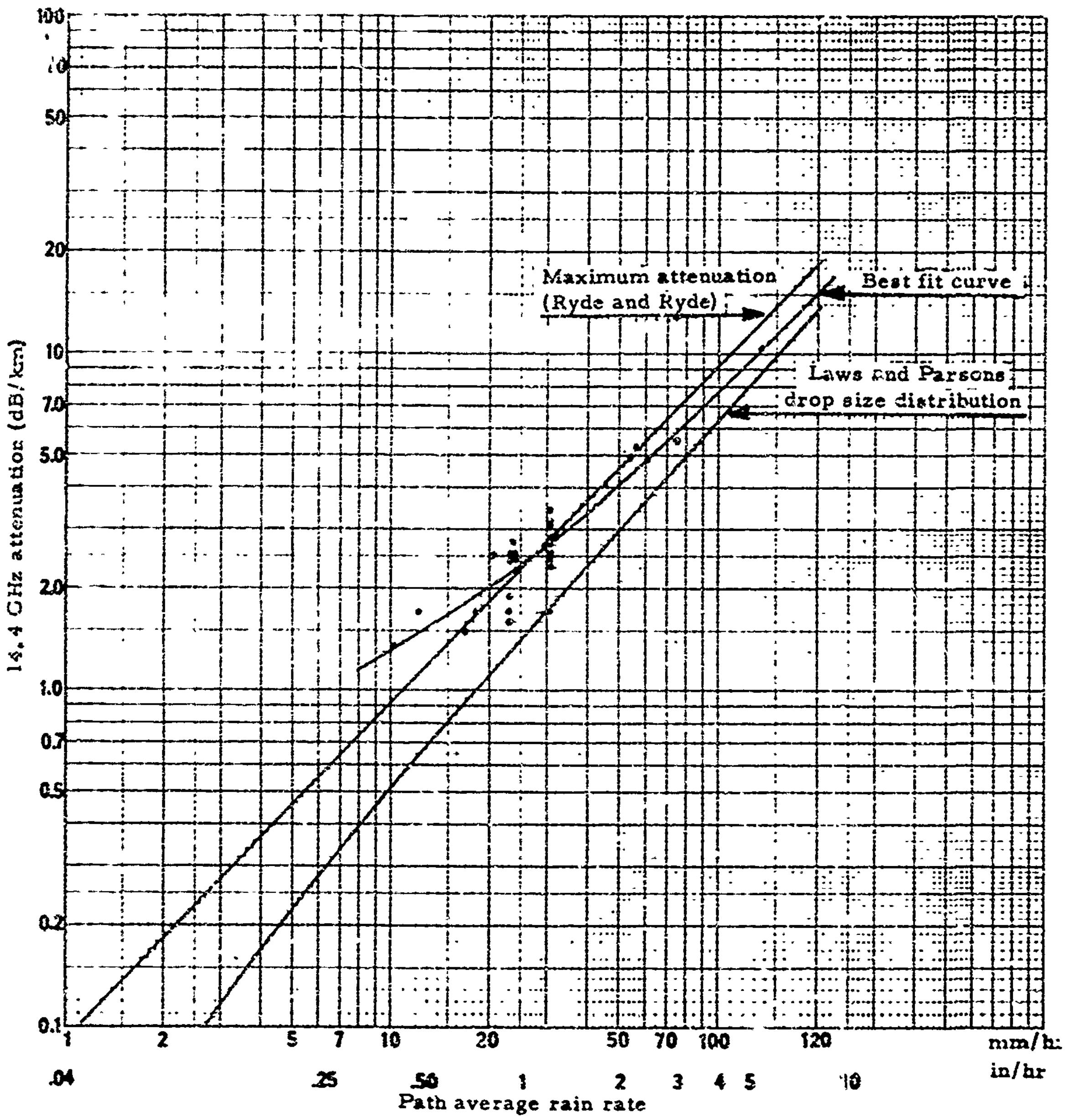

Figure 5. Measured rainfall attenuation at 14.4 GHz at Mississippi State Univ., February through May 1969 (Skerjanec and Samson, 1970).

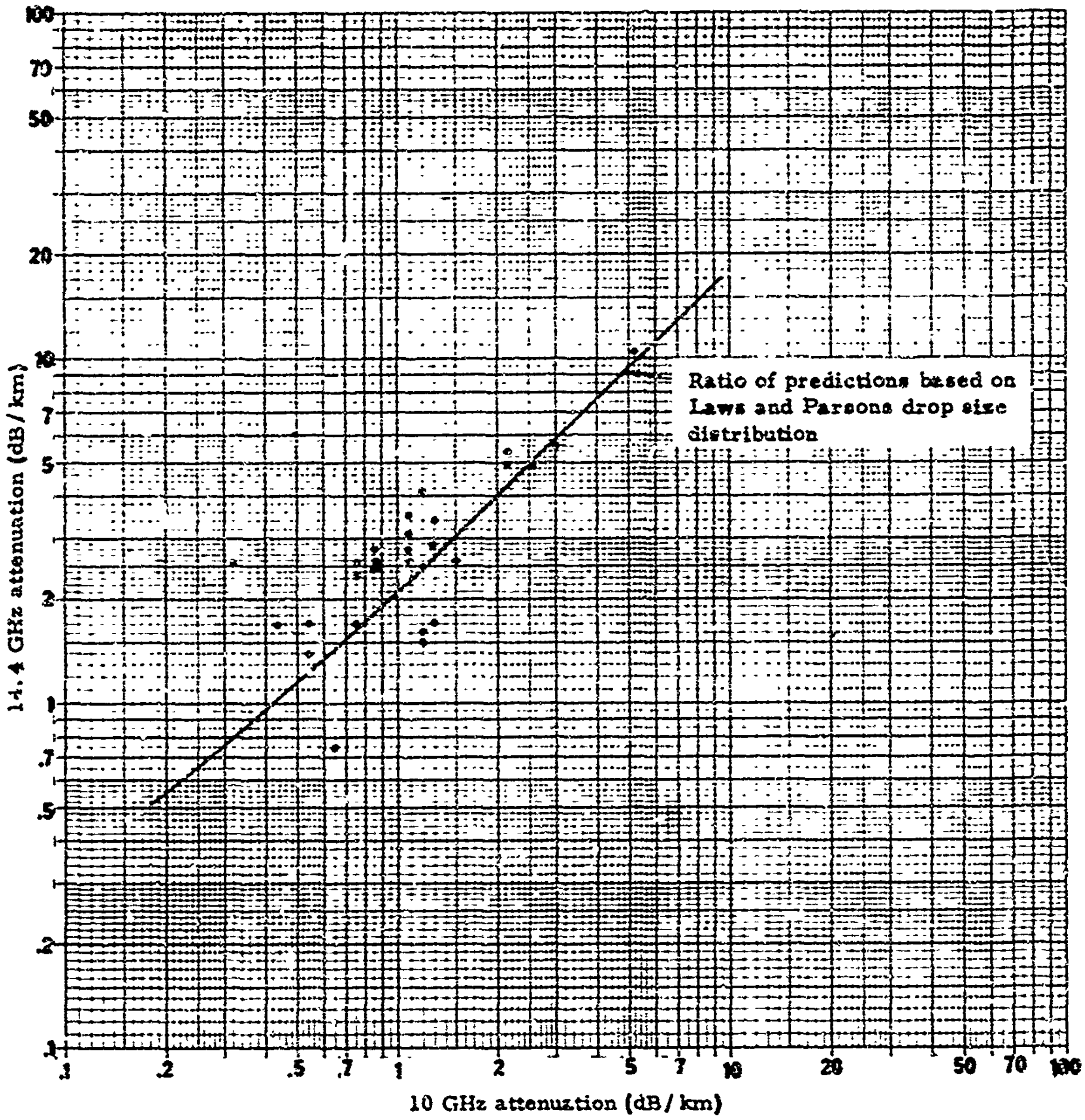

Figure 6. Relative attenuation at 10 and 14.4 GHz as measured at Mississippi State Univ., February through May 1969 (Skerjanec and Samson, 1970).

heavy rainfall generally occurs with frontal activity or squall lines, and in this case the rainfall zone is likely to extend well beyond 10 miles (16 km). Precipitation at a point varies partly because of storm movement and partly because of changes related to the life cycle of the storm. Thunderstorms tend to move approximately in the direction and with the speed of the winds several thousand feet above the surface; representative speeds are 20 mph for isolated storms and 30 mph for the squall-line variety. The duration of rainfall in a single thunderstorm is usually about 40 to 60 min, but the most intense rainfall usually lasts no more than 10 to 15 min. An analysis of rain outages over a 4-yr period on the 11-GHz TJ microwave relay systems (A. T. & T., 1964) indicated that about 50 percent of all outages lasted 8 min or less, and only a few percent lasted as long as an hour.

Kirby and Samson (1969), in a study of 7.5 GHz relay systems, found that heavy rainfall could cause outages of more than an hour on a multi-link system when the rain area moved along the system (from link to link), although the outage on a single link was about 10 to 15 min.

Freeny and Gabbe (1969) made a study of 27 rainstorms that occurred in a 6-month period in 1967, including nine classed as heavy. The data analyzed were obtained from 96 fast-response rain gages located approximately 1.3 km apart in a 13 by 14 km area in New Jersey. They determined that heavy rains have a "range of influence" of about 16 km, i.e., the separation at which the rain rate at a point "there" becomes relatively independent of the rain rate "here." When it was raining heavily at one station it was also likely to be raining heavily at nearby stations, but when it was raining lightly at one station it was unlikely to be raining heavily at stations 1.3 km away. As the rain rate at one station increased, it became increasingly

more likely to be raining heavily at nearby stations. The joint probability that a rain rate exceeding a given value would occur simultaneously at two stations was found to decrease rapidly as the separation between stations was increased, and it passed through a minimum at about 12 km.

Hogg (1969) made additional studies of the data from the New Jersey network to determine the probability of rain at various rates over paths of various lengths. For rates up to about 50 mm/hr, he found that the probability was about the same for any path up to 10.4 km; that is, the point rate was about the same as the 10.4-km path rate. At higher point rates, the probability of a given rate at a point became progressively higher than the probability on even a short path, e.g., at 100 mm/hr the 10.4-km path probability was less by a factor of 10 than that for a point. For a 10^{-5} probability (about 5 min/yr) Hogg found a point rate of 165 mm/hr, a 1-km path rate of 135 mm/hr, and a 10.4-km path rate of 80 mm/hr.

Since the studies of the New Jersey network are based primarily upon an analysis of only nine heavy rainstorms, which constitute a relatively small sample, direct extrapolation of the results to other areas may not be completely justified. As mentioned by Hogg, the dimensions of a rain cell with a given rain rate may be different in other areas. There could also be seasonal or air mass differences that would not be apparent from a study of only a few months data.

Empirical relationships between "area" and "point" rainfall have been developed by the Hydrologic Services Division of the Weather Bureau (1958) for durations between 30 min and 24 hrs. These relationships were used by the ETAC (Environmental Technical Applications Center, 1968) to estimate the average 10-mile ground

track rainfall from the point rainfall as follows: The 10-mile ground track rainfall is estimated to be 0.72 times the 10-min average, the point value is assumed to extend over about 4 miles of the track, and the remaining 6 miles has a rate 0.53 times the point rate. The lighter 6-mile rate is also continued for path extensions from 10 to 20 miles, making the 20-mile average rate 0.62 times the point or 4-mile rate. The report comments, "It is quite likely that the heavy rainfall cases in the U. S. are associated with squall lines rather than randomly distributed cells. In such a case the heavy rainfall rates characterized by the 10-min point rainfall might extend along the whole 20-mile ground track if the squall line were directly lined up with the track." The report further suggests that for a random orientation of a squall line with a radio path the most likely length of path affected by rain would be 7.1 miles, over which the point rate would be applied.

Squall lines or wide-area groupings of thundershowers are by no means unique to the United States and can occur in many parts of the world. Forsdyke (1960), in discussing synoptic weather of the tropics, stated that the intertropical front was at times associated with a line or narrow zone of bad weather, and that "disturbance lines" in West Africa traveled from east to west and were often associated with violent squalls. J. R. Clackson of the Nigerian Meteorological Service (1960) observed that these West African disturbance lines had a structure similar to the squall lines of the U. S.

Although at one time the monsoon rains were considered to be largely sealed off from outside influences and characterized by great steadiness, Riehl (1954) has described fluctuations or disturbances occurring during the monsoons of Southeast Asia. There is a tendency for a large fraction of the total rainfall (in areas affected by the monsoonal flow) to fall on only a few days out of a month, and

these heavy rains generally occur in a narrow zone along a traveling disturbance or trough line.

Rakshit and De (1964) studied the pre-monsoon thundersqualls of West Bengal and Assam; these were found to originate in scattered cells that formed along a line of discontinuity in the surface wind and developed into a solid line. These squall lines moved at speeds of 20 to 60 km/hr, lasted for 3 to 10 hrs, had cloud tops up to 16 km, and were frequently accompanied by hailstorms. The characteristics of these Indian squall lines are very similar to what might be observed in a squall line of the central U. S.

The intertropical convergence zone (ICZ) is the boundary between the trade wind circulations of the Northern and Southern Hemispheres, and in Southeast Asia it forms the boundary between the northeast and southwest monsoons. It is frequently nearly stationary but marked by lines of towering cumulus and thunderstorms. As the ICZ moves northward, marking the approach of the southwest monsoon, squall lines tend to form along and ahead of it, with buildups as high as 55,000 ft, and heavy rainfall along these lines sometimes persists for several hours (1st Weather Wing, 1965).

In addition to the uncertainties related to short-period rate fluctuations and the horizontal extent of rainstorms, there are considerations related to the usual climatological data that can have an important bearing on the accuracy of attenuation estimates. Rainfall statistics are based upon sampling networks, rather than on precise measurements. Most official raingages are rather widely separated compared with the extent of shower-type precipitation, and so it is unlikely that the most intense part of a storm is sampled by the normal gage networks; therefore, most climatological data probably tend to show a somewhat lower incidence of extreme rain rates than has actually occurred in any given area.

4. RAIN ATTENUATION ESTIMATES (U. S.)

The attenuation at a given time on a particular path depends upon the instantaneous path average rainfall rate. Rainfall statistics generally available are for rain at a point, and the shortest interval is 1 hr, although extreme values for shorter periods have also been tabulated for hydrologic studies (e.g., when the 5 min amount exceeds 0.25 in, or the 30 min amount exceeds 0.50 in).

Because rainfall normally varies considerably over 1 hr, an attenuation estimate based upon average hourly rates would not be satisfactory. Bussey (1950) developed a method of relating rainfall statistics to the rates for periods as short as 1 min, based upon an analysis of coincident data for various intervals. He also suggested that point rates for various intervals were equivalent to path rates for various path lengths, because of the size and movement of rainstorms; a 1-min rate at a point is equivalent to a 1-km path rate, 5-min data apply to a 3-km path, 10-min data to an 8-km path, 30-min data to a 25-km path, and 1-hr data to a 50-km path.

Hathaway and Evans (1959) developed a method of estimating rain attenuation at 11 GHz, based upon the ideas of Bussey and their own measurements over 1 yr in Alabama. Recently the method has been extended to frequencies as high as 36 GHz (Collins, 1969) through application of the theoretical work of Ryde and Ryde (1945) and Medhurst (1965).

A similar method has been proposed by Skerjanec and Samson (1970) for estimates at 10 and 15 GHz, based upon measurements obtained at 10 and 14.4 GHz over 4 months in northern Mississippi. Hogg (1969) has made estimates of the 18 GHz attenuation for various path lengths in Florida, North Carolina, New Jersey, Oregon, and England; his

rainfall probability estimates can be used to estimate attenuation at other frequencies by applying appropriate attenuation factors for the frequency of interest.

A comparison was made between the Skerjanec and Samson (S & S) and Collins estimates for 10 major terminal areas in various parts of the U.S., assuming a frequency of 15 GHz and a 40 dB margin. In addition, a comparison was made at four locations with an estimate derived from the precipitation and path length data given by Hogg (1969), using attenuation factors for 15 GHz as given by Skerjanec and Samson (1970). These comparisons are shown in table 3.

The "point" and "adjusted" values (Hogg, 1969) were obtained as follows: At Holmdel, N. J., the 1967 data show a point rainfall rate of 165 mm/hr at the 10^{-5} probability level; the equivalent path-average rates are 137 mm/hr (1.3 km), 127 mm/hr (2.6 km), 108 mm/hr (5.2 km), 92 mm/hr (7.8 km), and 82 mm/hr (10.4 km). Using the point rate of 165 mm/hr with the equivalent attenuation factor (S & S) yields a maximum path length of 3.2 km. If the equivalent path-average rate for a 2.6-km path is applied, the maximum path length will be 4.2 km, and the 5.2-km rate yields a maximum path of 4.7 km. The estimated maximum usable path at Holmdel should be between 4.7 and 5.2 km, or about 4.5 km. When the point rates are below 50 mm/hr, no adjustment is made.

The Hogg estimates for Miami, Corvallis, and Island Beach are based upon rainfall data obtained by the Illinois State Water Survey using a photographic technique that measures the drops in a small volume; the Holmdel data were obtained with a fast-response raingage network operated by the Bell Telephone Laboratories. The estimates by the Collins and S & S methods are derived from climatological data obtained by standard gage networks of the U. S. Weather Bureau.

Table 3. Predicted Maximum Usable Path Length for a 15-GHz Link With 40-dB Fade Margin

Location	S & S Rain Index	Collins Rain Region	0.001% of time (5 min/yr) in km: S & S	Collins	Hogg Point	Hogg Adjusted	0.01% of time (53min/yr) in km: S & S	Collins	Hogg Point	Hogg Adjusted
New York, N. Y.	4.4	E	5.5	16.1			10.1	21.2		
Washington, D. C.	5.0	D	4.9	12.5			9.0	18.2		
Chicago, Ill.	4.5	E	5.4	16.1			9.8	21.2		
Los Angeles, Calif.	2.1	H	10.6	23.8			18.4	29.8		
Seattle, Wash.	1.3	H	16.7	23.8			26.2	29.8		
Salt Lake City, Utah	1.7	H	13.6	23.8			22.0	29.8		
Kansas City, Mo.	4.7	D	5.2	12.5			9.6	18.2		
Minneapolis, Minn.	4.5	E	5.4	16.1			9.8	21.2		
Dallas, Texas	5.2	D	4.7	12.5			8.8	18.2		
Miami, Florida	6.0	C	4.1	9.3	1.1	1.7	7.6	14.1	2.4	3.1
Corvallis, Oregon	2.0	H	11.0	23.8	19.1	19.1	19.0	29.8	30.8	30.8
Island Beach, N. J.	4.6	E	5.3	16.1	3.8	5.7	9.8	21.2	11.8	11.8
Holmdel, N. J.	4.5	E	5.4	16.1	3.2	4.5	9.9	21.2	7.4	9.3

The stations selected for the comparisons shown in table 3 provide a reasonably good cross section of U. S. climatic types. In all cases, the S & S estimate is less than that obtained by the Collins method, usually by a considerable amount. For Island Beach and Holmdel, the S & S estimate is reasonably close to the adjusted Hogg value, but at Miami, the S & S value is much higher than the Hogg value. At Corvallis, the S & S value is lower than either of the other two estimates. The differences between the S & S and Collins estimates of path length are related mainly to differences in the attenuation factor selected for various rainfall rates. The Collins method is based upon an extension of the 11 GHz data of Hathaway and Evans (1959) to frequencies up to 36 GHz, by using the theoretical approach of Ryde and Ryde (1945) and Medhurst (1965). The S & S method is based upon measurements made at 10 and 15 GHz in Mississippi in 1969, which showed higher attenuations than the theoretical estimates based upon Laws and Parson's drop size distributions, particularly at rates below about 25 mm/hr (see fig. 5).

The required range of an approach system is 20 miles (32 km), and the desired range is 30 miles (48 km). Table 3 shows that none of the estimates, for any of the sites listed, is up to the required range at either the 5 or the 53 min/yr outage levels. The tabulated data are based upon a margin of 40 dB, but any reasonable increase in margin would not change the overall picture significantly. At 10 GHz the attenuation at the higher rainfall rates is approximately half what it is at 15 GHz, so by switching to 10 GHz the distances shown in table 3 would be roughly doubled; this would still not provide the required range at all locations.

5. RAIN ATTENUATION ESTIMATES (WORLDWIDE)

Rain attenuation estimates for other parts of the world usually depend upon some means of comparison with estimates for the U. S. Even 1-hr rainfall rate statistics are not generally available throughout the world, and in many areas only monthly or annual totals are readily available. A number of methods have been devised for estimating the short-period rainfall probability from climatological data such as the mean annual rainfall, the number of days with measurable precipitation, the number of days with thunderstorms, and the potential evapotranspiration (see, for example, Cole and Sissenwine, 1955; Hershfield and Wilson, 1957; Russak and Easley, 1958; Burroughs, 1967; Winner, 1968; and ETAC, 1962, 1968).

A report by ETAC (1968) compared the rainfall at Miami, Fla., with that at Tavoy, Burma, as representing the heaviest rainfall rate probability in the U. S. and the world. Miami was selected from hourly precipitation records of the U. S. Weather Bureau; Tavoy was selected from worldwide airfield climatological summaries (USNWS, 1967), as being the airfield with the greatest annual precipitation. The hourly precipitation at Tavoy was estimated using the method of Winner (1968), which uses the ratio between the mean annual rainfall and the mean annual number of days with precipitation,* and a moisture index derived from potential evapotranspiration estimates. By way of comparison, Miami has an annual rainfall of about 60 in, 127 days/yr with precipitation 0.01 in or more, and the maximum observed 24-hr rainfall is 15 in.

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* "Days with precipitation" are tabulated according to different minimum rates in various countries; these vary from a trace up to 0.10 in. The U. S., Canada, and Great Britain use 0.01 in; many European countries use 1 mm (0.04 in), but some use 0.1 mm. Burma uses 0.10 in.

Tavoy has an annual rainfall of 215 in, 142 days/yr with 0.10 in or more, and a maximum observed 24-hr rainfall of 13 in. Miami has 77 days with thunderstorms, Tavoy has 95. From the hourly values shorter period estimates were prepared by a method similar to the one used by Bussey (1950). The resulting distributions are shown in figure 7 with a curve based upon tabulations of observed 10-min rainfall at Miami. For occurrence frequencies of less than about 1.7 hr/yr, the derived curve for Miami overestimates the rainfall rate, and one might infer that the same is true for Tavoy.

The 1-hr rainfall to be expected once in 2 yr is shown in figures 8 and 9. These are based upon analyses by the U. S. Weather Bureau (Hershfield, 1961) and by Brooks and Carruthers (1946). Note that the 1-hr rates on part of the U. S. gulf coast are as high as those expected in most other continental land masses and are exceeded only in small areas of equatorial Africa, Madagascar, India, and Indonesia. Assuming that the relationship between 1-hr rates and short-interval rates (up to a few minutes) is similar throughout the world, an estimate of attenuation can be derived through use of these maps and one of the prediction methods discussed in section 4. For example, suppose an estimate is desired of the attenuation or maximum usable path length at Tehran. Figure 9 gives a 1-hr rate in that area of 1 in/hr; from figure 8 a point is selected on the 1 in/hr isoline in the U. S., such as Pueblo, Colorado. Then a path length prediction for Pueblo will be equivalent to the desired path length in the Tehran area.

Figure 10 shows the estimated two-way attenuation at 9.4 GHz for paths near Washington, Bombay, or in Laos (Krason, 1970). These curves are based upon rainfall estimates by ETAC (1962) and the correlation methods of Bussey (1950).

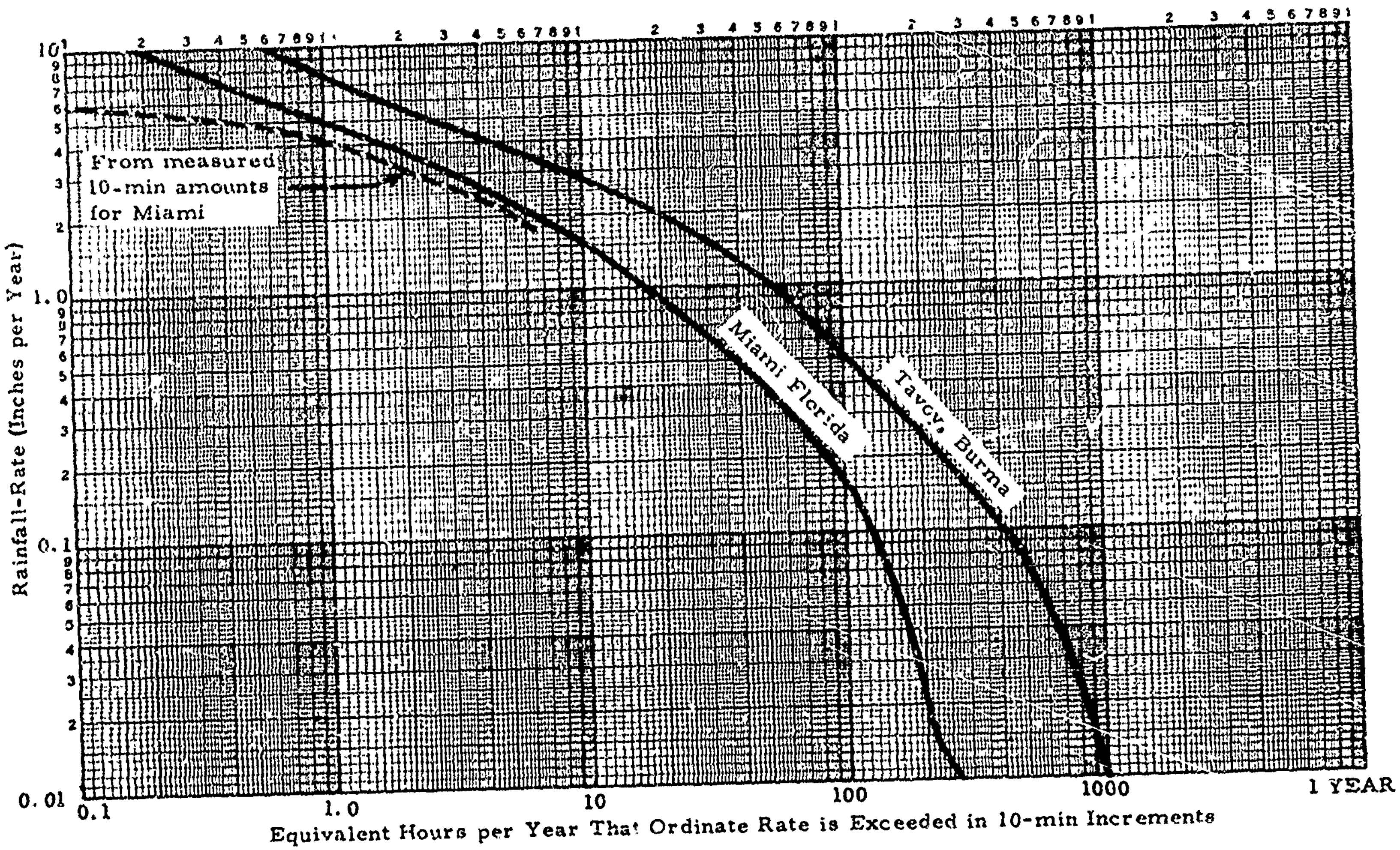

Figure 7. Cumulative distribution of 10-min point rainfall at Miami, Florida, and Tavoy, Burma. Solid curves are estimates derived from hourly amounts (ETAC, 1968).

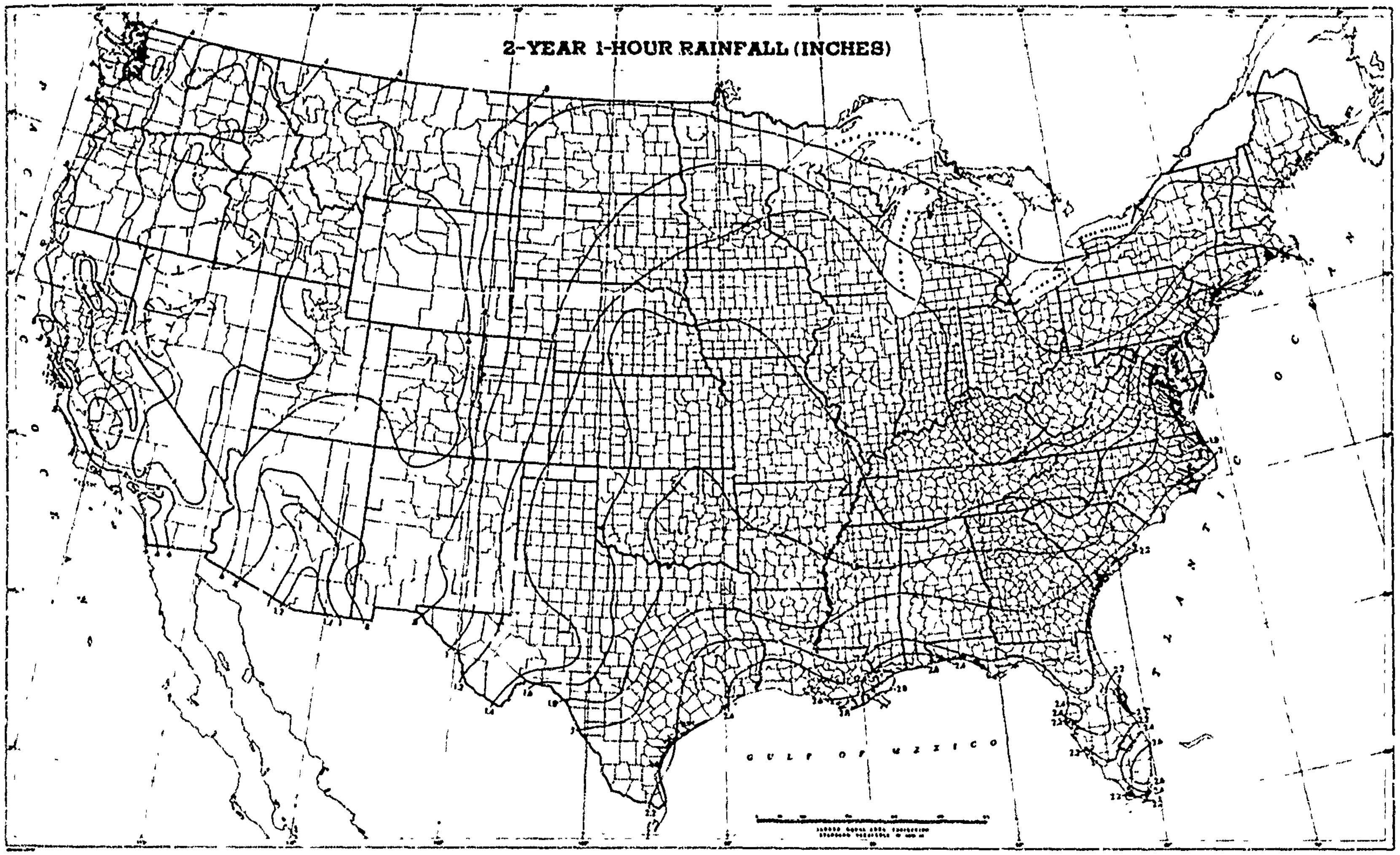

Figure 8. Maximum rainfall (in inches) in 1 hour expected once in 2 years (Hershfield, 1961).

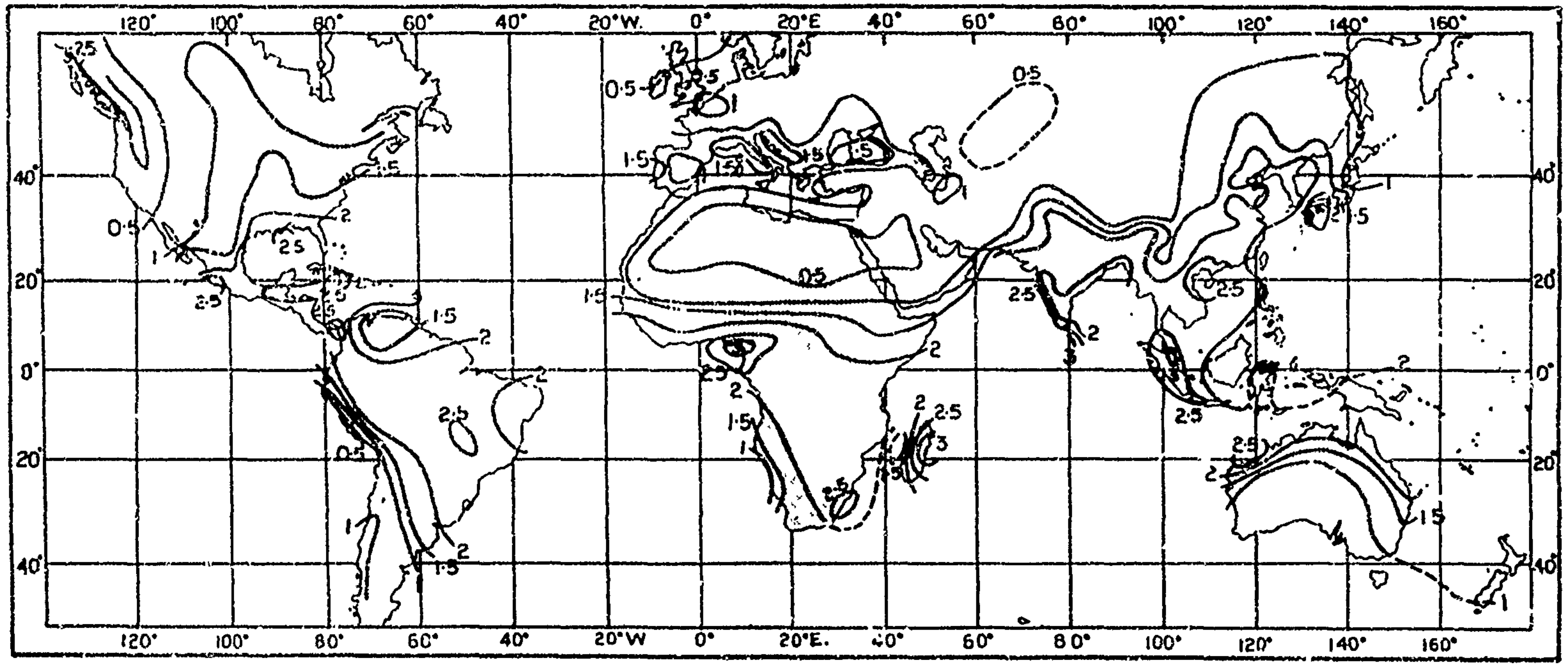

Figure 9. Maximum rainfall (in inches) in 1 hour expected once in 2 years (from Durst, 1949, based on Brooks and Carruthers, 1946).

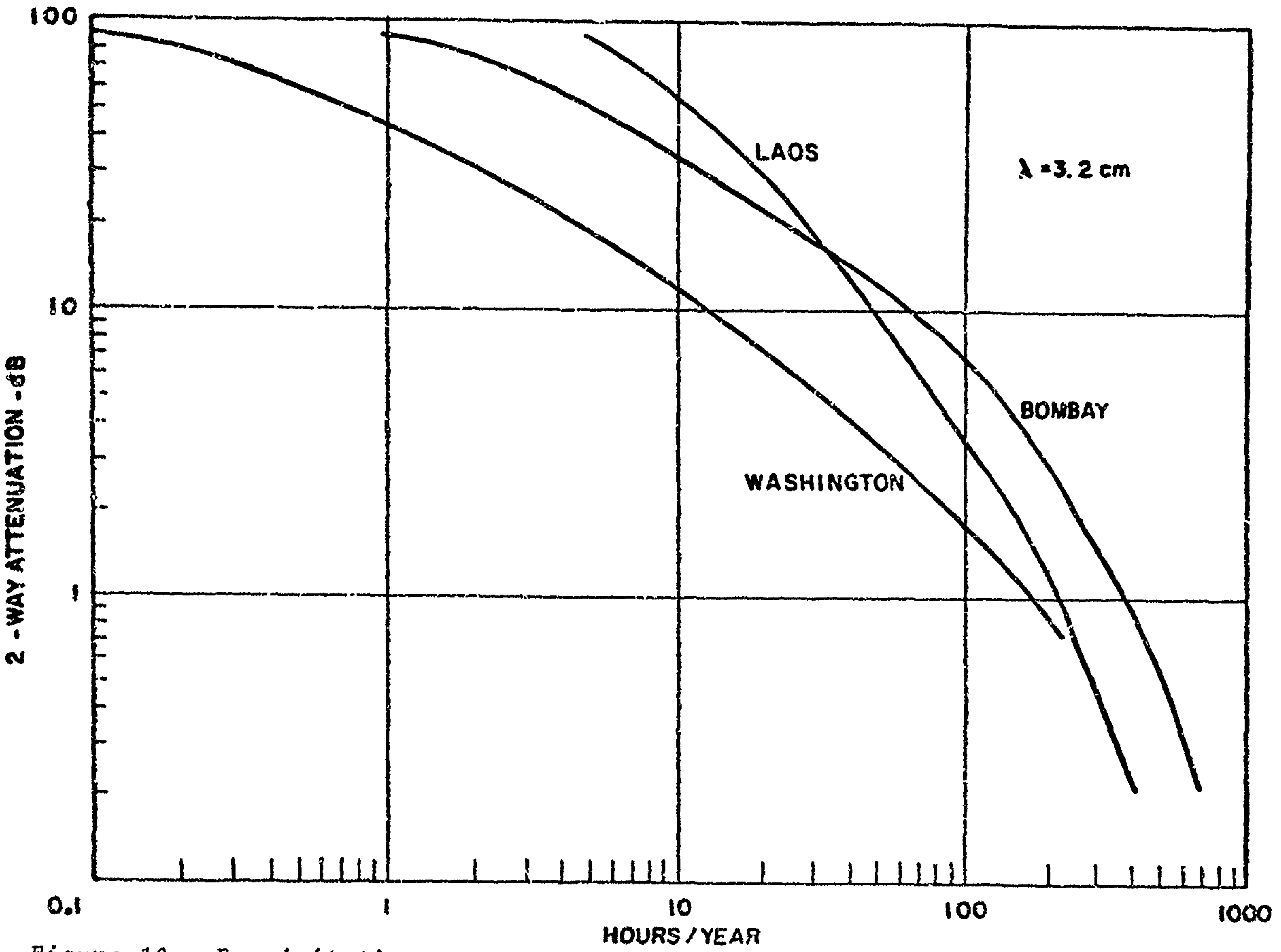

Figure 10. Precipitation attenuation equalled or exceeded per year on a path length of 20 nautical miles at 9.4 GHz (Krason, 1970).

6. THE EFFECT OF ATMOSPHERIC REFRACTION ON APPROACH SYSTEMS

The density of air normally decreases with height, but the atmosphere is never static; so there will always be changes in density, both vertically and horizontally, along a radio path. The speed of a radio wave varies inversely with the density of the medium through which it travels, and the radio refractive index of air is the ratio of the speed of propagation of a radio wave in a vacuum to its speed in the atmosphere under given conditions of pressure, temperature, and humidity. This ratio, n, is approximately 1.0003 under standard conditions near the earth's surface. For convenience, a scaled up value, N, or refractivity, is normally used in propagation studies; this may be obtained from the following formula (Smith and Weintraub, 1953):

$$N = (n - 1)\,10^6 = \frac{77.6}{T}\left[P + \frac{4810\, e_s\, RH}{T}\right]$$

where	P	=	pressure in millibars
	T	=	temperature in degrees Kelvin
	e_s	=	saturation vapor pressure in millibars
	RH	=	relative humidity in percent.

At sea level, N values range from about 280 to 410 N-units, but it is the vertical gradient of refractivity that is of greatest concern to propagation, rather than the absolute value at a point. Horizontal changes in refractivity also occur, but, because horizontal gradients

are generally very much smaller than vertical gradients, they are usually neglected in estimating propagation along microwave paths.

Atmospheric pressure, temperature, and humidity normally decrease with height, and in the so-called "standard" atmosphere the refractivity also decreases with height. A decrease of 40 to 50 N-units/km is considered a normal condition--about what might be expected near noon on a clear, cool day; the 4/3 earth radius concept used in radio propagation calculations is based on a decrease with elevation of 39 N-units/km. Radio waves are refracted (or bent) in the direction of increasing density of air and increasing water vapor content; therefore, a negative refractive gradient causes the waves to bend toward the earth. Approximately 30 percent of the total bending occurs in the first 100 m (for rays at an elevation angle of 0^{o}), and 60 percent takes place in the first kilometer above the earth's surface (Bean and Thayer, 1959).

The normal condition of the atmosphere causes a wave front traveling tangent to the earth's surface to bend in the same direction as the earth's curvature, thus, the radio horizon is somewhat extended beyond the so-called line-of-sight horizon. Very frequently, however, the atmosphere departs markedly from this normal condition, and so does the direction and intensity of the bending.

Abnormal atmospheric conditions can cause:

Subrefraction (also known as the "earth bulge" condition) where the increase of N with height (positive refractivity gradient) causes radio waves to bend upward;

Superrefraction where larger than normal negative gradients cause the waves or individual rays to bend sharply downward;

Ducting (an intense form of superrefraction) which may essentially "trap" the rays as though in a waveguide. Superrefractive gradients

usually increase the range of radio signals, whereas ducting gradients may cause either a large increase in signal range or a complete loss of signal; this depends on the location of the antennas relative to the duct (see Dougherty, 1968).

For convenience in discussion, the various refractive gradients are defined as follows:

Subrefractive:	$dN/dh > 0/km$; radio waves refracted upward.
Normal:	$0 > dN/dh > -100/km$; waves refracted slightly downward.
Superrefractive	$-100/km > dN/dh > -157/km$; waves refracted sharply downward.
Ducting:	$dN/dh < -157/km$; waves may follow the earth's curvature.

6.1 Subrefractive Gradients

Subrefractive layers may be elevated or ground based; however, Type A subrefraction (Bean et al., 1966), associated with strong incoming radiation found in arid and semi-arid climates during daylight hours, is always ground based. It usually occurs with temperatures above 30°C and relative humidities below 40 percent in warm, dry continental locations, but superadiabatic temperatures can be found (sometimes so extreme that the air density increases with height) with temperatures above 10°C in elevated plateau locations where bare ground has been heated day after day by perpendicular rays of the sun. In subrefractive cases this density inversion is usually combined with a water vapor inversion, because a layer of absolutely unstable air tends to concentrate the available water vapor near the top of the layer.

Type B subrefraction occurs most commonly from evening through early morning and is characterized by both temperature and water vapor inversions. It is associated with surface temperatures between 10°C and 30°C and relative humidities above 60 percent; temperatures and humidities are slightly lower when it occurs in an elevated layer. It is found in the evening in dry regions and during the night or early morning in moist locations.

In dry regions (including the hot period of temperate climates) the evening occurrence of Type B subrefraction may be called residual Type A subrefraction, since it is caused by moisture that was convected aloft during the day and trapped near the top of the layer by a stable stratified cap which develops as the temperature profile becomes modified at both top and bottom after sunset (when the outgoing radiation exceeds the incoming radiation). It is more typically found in plateau valleys than coastal locations.

In moist regions (tropical rain-forest or the wet season of wet and dry or warm continental climates) the ground acts as a moisture sink during the night or early morning and creates a water vapor inversion, which is usually maintained until sunrise because of the stable conditions near the ground. Coastal areas, where differential heating of land and sea forms a surface layer of air that is cooler and less humid than the layer above it (e.g., conditions preceding a land breeze), are subject to ground-based subrefraction. Sometimes these layers form or are lifted above the surface and become elevated; often they are found above a surface superrefractive layer just before vertical mixing begins.

Frontal passages and other synoptic changes, when combined with elevation effects, can often lead to subrefractive conditions, e.g., subrefractive gradients can be found in upslope conditions formed by a moist, warm air mass pushing up against a mountain range. Substandard

gradients, causing reduced radar ranges and far below average signal strengths, are common to many fog situations, particularly when warm moist air moves over nocturnally cooled ground. Such fogs may be radiative or advective or a combination of both types. An example would be fog created when relatively warm marine air is transported over low coastal hills into a valley filled with cool air. However, some types of fog are associated with superrefractive or ducting gradients; an example is steam fog, which is formed when cold air passes over a warm sea (or warm water-soaked soil).

6.2 Superrefractive Gradients

Superrefractive and ducting gradients in ground-based layers are most often associated with temperature inversions, not only because a positive temperature-height gradient causes a negative N-gradient, but also because the stability associated with a temperature inversion often leads to a steep negative gradient of humidity through the inversion. There are two other typical situations common to certain climatic areas that produce strong ground-based gradients. In arctic regions, where surface temperatures are colder than $-20^{\circ}C$, and there is a very strong low-level inversion, the humidity, which is almost negligible, may remain constant or increase with height. In tropical regions, where the temperatures are higher than $25^{\circ}C$, and the air moisture is strongly influenced by large bodies of water, the temperatures may slightly decrease with height, but the major gradient change is caused by a very strong lapse of absolute humidity (although the lapse of relative humidity may be small).

The most favorable conditions for superrefraction occur in slow-moving high pressure systems (usually associated with subsidence): clear skies (permitting nocturnal cooling), and calm or very light winds

(conducive to thermal stratification of air near the ground). A source of surface moisture (lake, sea, river, or moist ground) increases the likelihood of superrefractive layers. The least favorable conditions are found in the season of the year when deep low pressure systems, associated with cloudy, rainy weather and strong winds, move rapidly across the continents. In temperate climates the lowest incidence of superrefraction is in winter, but in the Arctic intense temperature inversions favor superrefraction during the winter. In tropical wet and dry climates (such as the southern tip of Florida) summer is influenced by the turbulence of the subtropical jet, but during winter the subtropical high pressure ridge creates areas of superrefractive gradients. The best times of day for superrefraction, regardless of season, would be just after sunrise and near sunset; the least probable time would be midday to mid-afternoon, because normally the warmest time of day has low relative humidities, convective mixing, and frictional turbulence.

6.3 Elevated Superrefractive Gradients

There are two major causes of elevated superrefractive or ducting layers. The most persistent (and most predictable) occurs in an area of general subsidence where a large mass of air is adiabatically heated as it descends from high levels. One of the best examples of this is the stable, or eastern portion, of large semipermanent high pressure cells, where the circulation causes the air to descend over water bordering the western coasts of continents. Considerable subsidence is also found in migratory slow-moving high pressure systems, warm sectors of upper air ridges, between a squall line and cold front, along the edge of a cold front moving slowly over a moist surface, and during certain occurrences of mountain lee winds; e.g., the foehn blowing over a moist coastal area. The heating of the subsiding air produces a

temperature inversion at varying heights above the surface; this acts as a lid on convective mixing, with the result that the air above the inversion is relatively dry compared with the air below the inversion (particularly over or near oceans or large lakes), and through the inversion layer the refractive gradient tends to be strongly superrefractive. Since these elevated inversion layers may form below 1 km, they could affect approach system beams, especially at coastal terminals.

The other major cause of elevated superrefractive layers is advection of drier continental air over moist land or sea surfaces, e.g., along certain portions of sea-land breeze systems or the top of fog or stratus as it lifts above cool surfaces. This form of elevated layer is usually closer to the surface, occurs more erratically, and is, therefore, harder to predict.

6.4 Effects of Subrefraction and Superrefraction

Subrefraction associated with intense solar radiation (Type A) would rarely be a problem in any ILS glide path, because the weather associated with it would maintain unlimited visibilities and ceilings; however, the residual Type A subrefraction (or evening Type B) could be a problem, because the lapse of humidity just above the top of the inversion could cause a superrefractive layer. These layers would normally be under 500 m and would change a downward shift of the radar beam to a sudden upward shift as the plane passed from the superrefractive to the subrefractive gradient. Fortunately, this type of subrefraction (residual) is not too intense.

As an example of the effects of a superrefractive layer versus a normal layer, consider the case of a transmitter-receiver link with both antennas 20 m (66 ft) above the surface. If the gradient of the ground-based layer (from 0 to 100 m above the surface) is -47 N/km,

the radio horizon would be 24.4 miles; if the gradient is -100.5 N/km, (barely superrefractive) the maximum distance of line-of-sight transmissions would be 33.0 miles, 35 percent more than the normal horizon; and, if the assumed gradient is increased to -143 N/km, the radio horizon would be extended 166 percent (to 65 miles). These extensions are significant for problems of radar coverage and ground-to-air communication links; however, these results are for a transmitter initial elevation angle near 0°, where the bending is much greater than would be expected with normal approach path elevations (2° to 4°).

6.5 Angular Dependence of Refractive Bending

There is very little frequency dependence for refractive bending below about 30 GHz, but the angle at which a radio ray intercepts a particular refractive layer limits the amount of bending that occurs as the ray passes through the layer. Burrows and Attwood (1949) state that, "Both theoretically and practically it has been found that the effects of nonstandard refraction are negligible for rays that leave the transmitter at an angle with the horizontal of more than about 1.5°. Rays that leave at an angle with the horizontal of less than 1.5°, and especially those emerging at angles with the horizontal of 0.5° or less, are strongly affected by nonstandard refraction." Bean and Cahoon (1957) found that atmospheric bending did not appear to be a sensitive function of the refractive profile at angles greater than 1°, and in most cases the bending could be approximated by a linear function of the surface refractivity for elevation angles greater than 10 mrad (0.6°). Thus, for approach systems with a glide slope between 2° and 15°, the effect of abnormal refractive gradients should be minimal; however, in areas where very strong gradients are known to occur frequently, and

particularly if operation below 2° is contemplated, the possible influence of refractive bending on system operation should be considered.

Climatic and geographic factors related to the frequency of occurrence of the various types of refractive gradients are summarized in the appendix. Graphs are included showing the distribution of observed gradients, based upon an analysis of RAOB data for 5 years at nine U. S. terminal areas (only 2 years' data at Joliet).

Figures 11 through 14 are ray tracings for approach angles of 2° and 4° above the horizontal; they are based upon a true earth profile with a vertical exaggeration of 10 to 1. In a homogeneous atmosphere the rays would all be straight lines; any refractive bending in a stratified atmosphere is shown by a departure from a straight line. The individual rays are separated by 1 mrad, so that the outer rays in each bundle are about 0.23° from the beam center ray.

The refractive profiles are to the right of each graph; these were arbitrarily chosen to illustrate the effects of the various types of gradients previously defined. Figure 11 has a subrefractive layer (+175 N-units/km) 100 m thick; figure 12 has a normal gradient (-40 N-units/km) over the entire profile; figure 13 has a surface-based superrefractive layer (- 5 N-units/km) 100 m thick; and figure 14 has an elevated duct (-300 N-units/km) 200 m thick based at 500 m, with slight subrefraction in the lowest 100 m. Note that the gradient in figure 13 exceeds the value defined as ducting (-157 N-units/km), so that this could be considered a case of surface ducting.

At these elevation angles, it appears that refractive displacement of the approach path will be very small, even at 35 km. The total bending will be progressively less as the distance from the transmitter is reduced, i.e., displacement from the normal or calibrated position will be much less at 10 km than at 35 km.

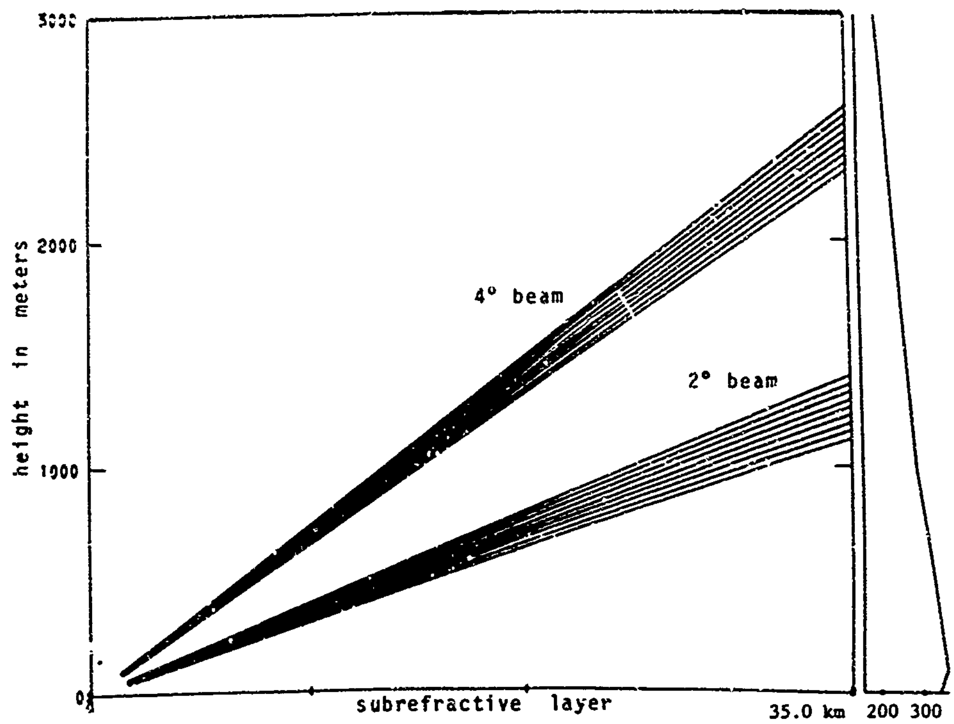

Figure 11. Ray tracings with subrefractive layer in lower 100 m.

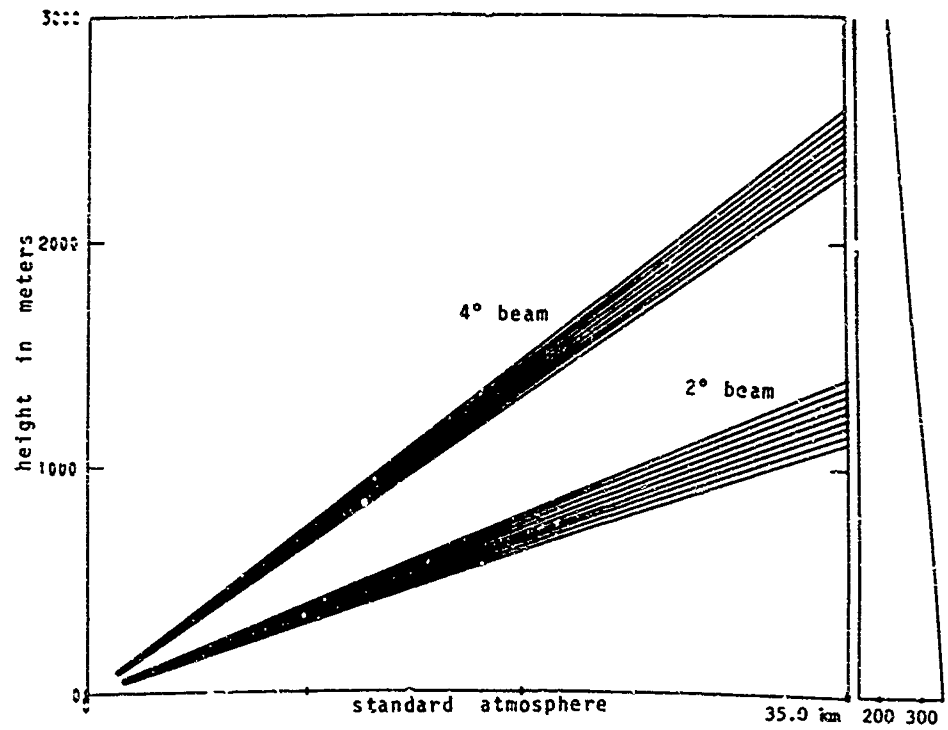

Figure 12. Ray tracings with normal gradient.

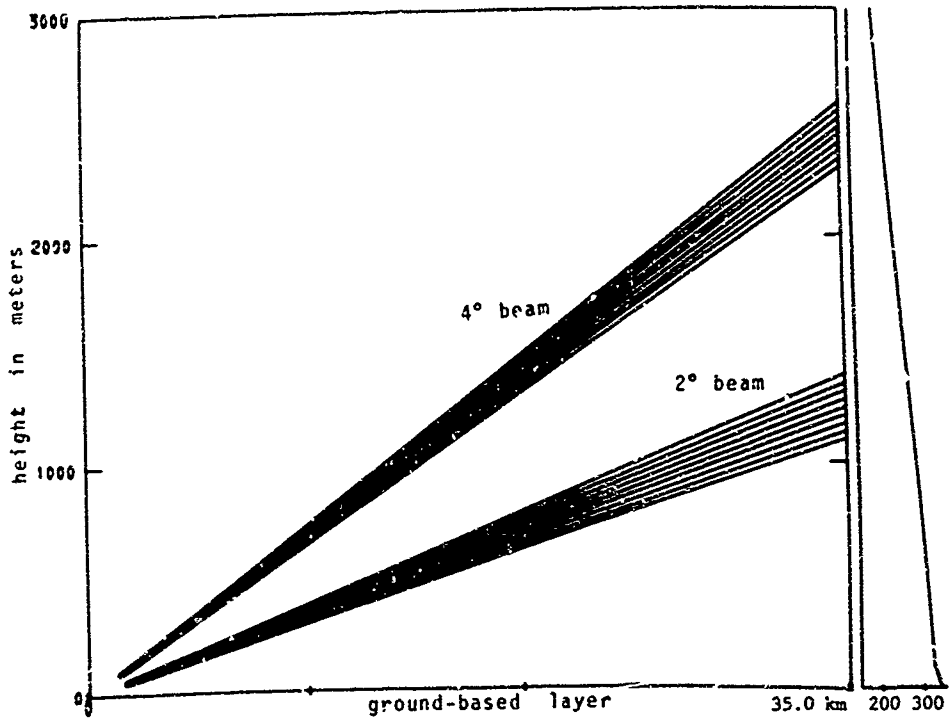

Figure 13. Ray tracing with superrefractive layer in lower 100 m.

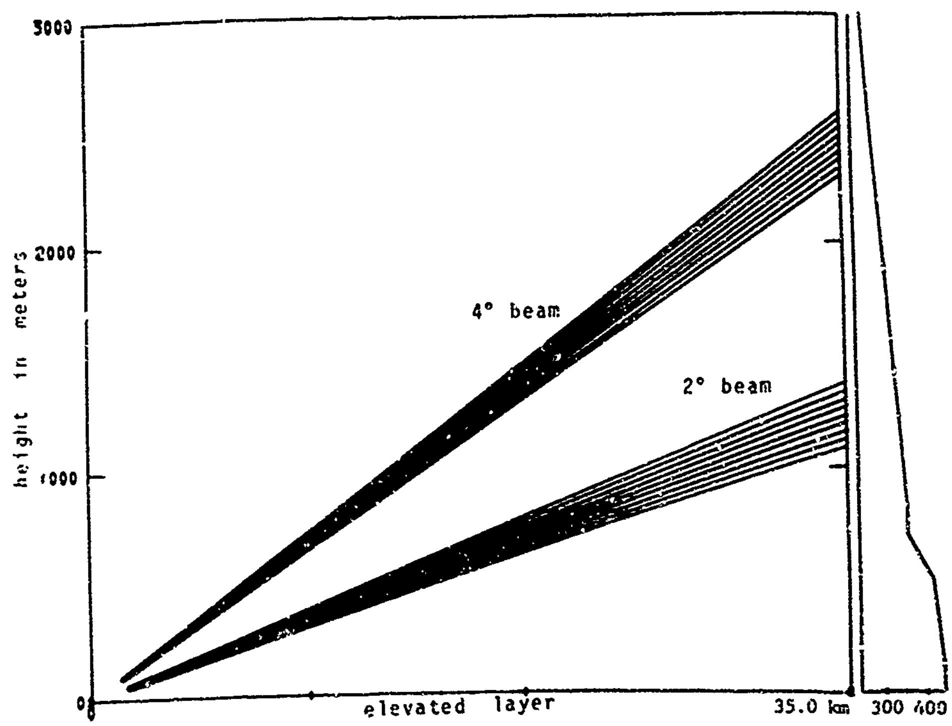

Figure 14. Ray tracings with elevated duct at 500 m.

7. WEATHER PHENOMENA ACCOMPANYING HEAVY RAIN

The primary effect of heavy rainfall on an approach and landing system is the attenuation of the radio signals. There are other possible effects, however, that are related to the thunderstorms that normally produce the heavy rain; these include wind shear, gustiness, turbulence, hail, and changes in temperature, pressure, humidity, ceiling, and visibility.

While a severe thunderstorm moves across an approach lane the near surface wind direction might vary by as much as 180°, and these changes could occur several times in the vicinity of the storm (Byers and Braham, 1949). These wind variations are related to the inflow and outflow from the storm cells and the prevailing large-scale wind flow in which the thunderstorm is imbedded. A cold downdraft develops in a region of heavy rain (in a storm cell), continues below the base of the cloud, and spreads out as it strikes the ground. The horizontal spread of this downdraft near the ground produces the gusty and shifting surface winds and low-level turbulence commonly observed. The degree of gustiness and turbulence is somewhat influenced by the terrain roughness; in relatively level terrain in Florida and Ohio observations by the Thunderstorm Project showed a turbulence maximum in the lowest 100 ft above ground (Byers and Braham, 1949). Wind speeds exceeding 90 mph in gusts have been observed in thunderstorms in the U.S., and, in general, the maximum gust speeds occur very close to the area of heavy rain.

Recent studies in other countries (Halaby, 1968) show measured speed changes of 15 mph/100 ft in the lower segments of approach paths. Wind shear of this magnitude close to the ground could cause serious alignment and control problems in the critical seconds

just before touchdown. Burnham (1964) mentions that aircraft with highly swept wings and/or low rolling inertias have relatively larger responses to turbulent conditions than do propeller aircraft. Litchford (1968) points out that the large aircraft of the "jumbo jet" type, have a more sluggish response than previous transport aircraft and may require additional time for the execution of "side - step" maneuvers to maintain runway alignment during adverse wind conditions.

The greatest turbulence in thunderstorms is associated with the highest water concentrations (Byers and Braham, 1949). In a vigorous updraft large quantities of water vapor can be converted to liquid water and when this falls as rain, strong downdrafts develop, which may reach speeds of 20 ft/sec or more. Thus, the conditions that are favorable for heavy rain, which may cause high levels of radio attenuation, are also favorable for heavy turbulence.

Hail is always a possibility near large thunderstorms, but the ratio of hail-to-thunderstorm frequency is relatively low. Reflections from hail shafts or from hail accumulations on the ground could cause undesirable bending of the approach system radio beam, but attenuation by hailstones is generally much less than for rain (Ryde and Ryde, 1945) at equivalent rates. Thunderstorms most apt to contain hail are also those with severe turbulence (Battan, 1959), because strong updrafts are a requirement for the formation of hail of significant size.

Short-period changes in temperature, pressure, and humidity may also be sizeable near heavy rainstorms. Temperature gradients of more than 20° F/mile (6.9° C/km) have been observed (Byers and Braham, 1949). These pressure and temperature variations could cause some error in pressure altimeter readings, but since some form of radio altimeter will probably be used on approaches, the pressure altimeter errors would be a minor consideration in system operation.

Visibility in the vicinity of thunderstorms is usually good, because of the prevailing instability and the turbulent mixing over great depths; however, in the rain shaft (beneath the cloud base) visibility may be seriously restricted. For example, Petterssen (1940) gives the following estimates of visibility in rain: heavy -- 1 to 4 km; very heavy -- 500 to 1000 m; tropically heavy -- 50 to 500 m. The latter is equivalent to the restriction expected with medium to thick fog, or heavy to very heavy snow.

Very low clouds or patches of fog that may form during or immediately after heavy rainfall have a relatively minor effect on microwave signals compared with the attenuation caused by rainfall. Ryde and Ryde (1945) calculated that the maximum attenuation from clouds or fog that restricted the visibility to 100 ft would be 0.23 dB/km at 10 GHz and 0.5 dB/km at 15 GHz. Gallaher (1969) observed attenuation of about 0.2 dB/km at 10 and 15 GHz during a heavy fog on a 5-km path in Mississippi (visibility 200 ft). Part of the signal reduction under fog conditions may at times be caused by subrefractive bending, rather than by absorption or scattering by the fog particles (Kerr, 1951).

Lowering of both the ceiling and the visibility can be expected during heavy rain. This results from a number of factors, such as, increasing saturation of air below the clouds from evaporation of raindrops, and lowering of the cloud base by downward air currents. New cloud layers are likely to develop in the very moist air near the ground, as a result of horizontal and vertical mixing. Austin (1960) concluded, from a radar study of precipitation intensity related to ceiling and visibility observed at two airports in Massachusetts, that although there was a tendency for ceiling and visibility to lower as the rain intensity increased, the relationship did not appear to be linear.

Goldman (1951) made an extensive study of the problem of ceiling lowering during continuous rain and determined that the ceiling lowered in a discontinuous fashion, apparently because the ceiling tends to remain nearly constant until a new cloud layer forms beneath the original cloud; a number of additional and progressively lower layers may develop in this fashion, thus lowering the ceiling in steps.

A study of 272 thunderstorms observed at Charleston, W. Va., over a 4-yr period showed that on the average only two thunderstorms/year reduced the ceiling to less than 500 ft and surface visibility to 1 mile or less, and these conditions lasted only for a brief period. Storms with wind gusts above 40 mph occurred about eight times/year and two storms/year had gusts of more than 60 mph (Weather Bureau, 1954).

Figure 15 compares the monthly occurrence of thunderstorm days (when heavy rain is a possibility) with the percentage of time that ceiling and visibility are below 200 ft and ½ mile. Indications are that the two factors are usually out of phase, i.e., low ceilings and visibilities are at a minimum during months of high thunderstorm frequency.

If snow occurs with thunderstorms, the precipitation is apt to be a mixture of rain and snow with a higher attenuation potential than the equivalent amount of water in the form of rain alone. During the seasons in which such occurrences are possible, the moisture supply available to the storm is normally much lower than during the summer, so the precipitation potential is lowered. An approach system designed to operate under the maximum summer showers in a given area should also provide satisfactory guidance during wet snow conditions. Ceiling and visibility under these conditions are frequently very low, however, so demands on the system may be high. Another factor to be considered is a possible change in glide path angle or beam thickness resulting from changes in ground reflections as the snow accumulates on the ground (Klass, 1969).

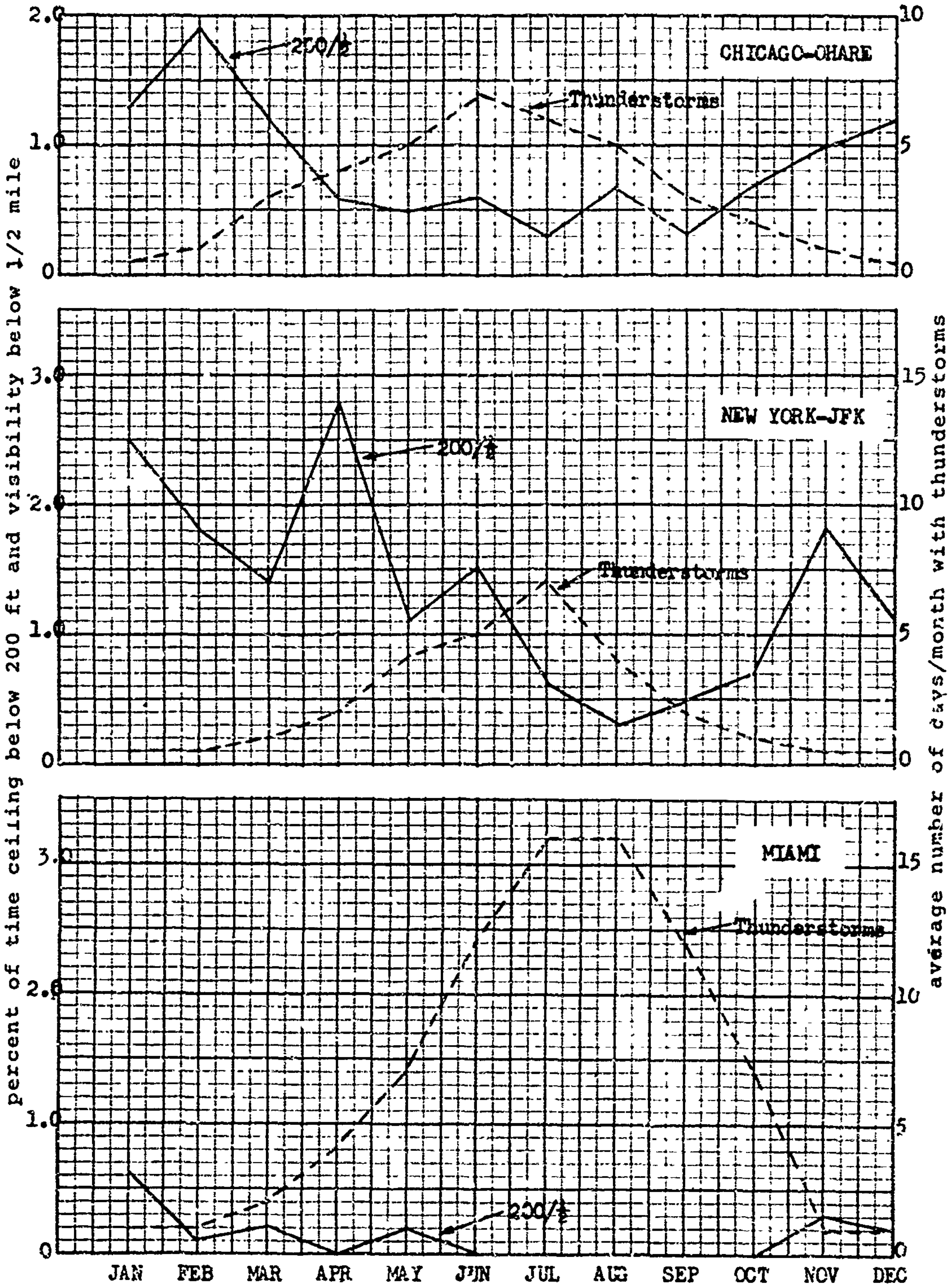

Figure 15. Annual variation in occurrence of thunderstorms and low ceilings and visibilities (200 ft and 1/2 mile) (after Harrison, 1964).

Table 4 lists some general weather characteristics for 16 of the major U. S. air terminals, such as, days with heavy fog or thunderstorms, observed and predicted rainfall rates, and percentage of time the ceiling is below 200 ft and visibility is below ½ mile.

8. CONCLUSIONS

Of the possible weather effects on approach systems operating between 5 and 15 GHz, rain attenuation is probably the most important. We found no mention in the literature of significant rain attenuation at 4 to 6 GHz, but Kirby and Samson (1969) found evidence that heavy rainfall caused outages on 25-mile radar relay links operating in the 7135 to 7630 MHz frequency range. A report to the F. C. C. by A. T. & T. (1964) stated that rain attenuation had been found not to be a source of outage on the TH systems (6 GHz), but on the TJ systems (11 GHz) rain attenuation caused propagation outages to the extent that short haul reliability objectives for the microwave relays were not met. Measurements indicate about twice as much attenuation from rainfall at 15 GHz as at 10 GHz, and the path length estimates discussed in section 4 indicate that a 15 GHz approach system could not provide high reliability over the required 20-mile range. From the standpoint of high reliability in areas having moderate to heavy rainfall, a frequency below 6 GHz appears to be the most desirable, and using frequencies above about 7.5 GHz would involve some trade-offs in terms of reliability.

For the most critical part of an approach--say, within 1 or 2 miles of touchdown--a 15 GHz system could be designed with sufficient margin to provide high reliability even in areas of heavy rainfall; thus, it might be useful for precise runway alignment or flare-out information.

Table 4. Climatological Data for Selected U. S. Stations

Station	*Av. Annual Precip. (in)	*Days per year with: Precip. 0.01 in or more	Snow or sleet 1.0 in or more	Thunder-storms	Heavy fog (visibility 5/16 mile)	#Maximum observed rain rate: 5 min in/hr	1 hr in/hr	@Expected rain rate once in 2 yr: 5 min in/hr	1 hr in/hr	%Time below 200 ft & ½mi: %
New York, N. Y. (JFK)	43.93	120	9	24	32	9.00	[illegible]	4.4	1.3	1.3
Washington, D. C. (DCA)	40.78	112	5	28	14	9.60	3.42	5.0	1.5	0.5
Chicago, Ill. (ORD)	32.78	120	11 (MDW)	37	14 (MDW)	7.68	2.81	4.6	1.4	0.8
Los Angeles, Cal. (LAX)	12.63	35	0	3	48	5.28	1.51	2.1	0.6	2.4
San Francisco, Cal. (SFO)	18.69	[illegible]	< ½	2	19	3.96	1.07	1.9	0.5	0.7
Seattle, Wash. (SEA)	38.94	162	5	8	53	3.48	0.84	1.2	0.3	2.5
Salt Lake City, Utah (SLC)	13.90	86	17	35	10	4.80	1.17	1.9	0.5	0.6
Denver, Colo. (DEN)	14.81	87	18	41	11	10.92	2.20	2.9	0.7	0.4
Kansas City, Mo. (MKC)	34.07	99	6	50	12	9.60	4.79	4.9	1.5	0.3
Phoenix, Ariz. (PHX)	7.20	34	0	22	2	5.16	1.41	2.5	0.6	
Minneapolis, Minn. (MSP)	24.78	111	13	36	11	9.72	2.27	4.5	1.3	0.5
Dallas, Texas (DAL)	34.55	79	1	41	8	14.16	3.76	5.1	1.8	
New Orleans, La. (MSY)	53.90	112	< ½	70	33	12.00	4.71	6.1	2.1	1.3
Atlanta, Ga. (ATL)	47.14	115	< ½	50	28	10.56	3.23	5.0	1.6	1.1
Miami, Fla. (MIA)	59.76	127	0	77	7	8.52	4.53	6.0	2.3	0.1
Mobile, Ala. (MOB)	68.13	123	< ½	81	36	10.68	3.51	6.0	2.1	

* 1931-60 normals (USWB, 1967)

\# At least 5-yr record (Jennings, 1963)

@ (USWB, 1955)

% (Harrison, 1964)

Very few measurements have been made of the attenuation by snow when the path precipitation rate (water equivalent) was well defined. Takada and Nakamura (1966) and Bell (1967) have indicated that attenuation by wet snow (or by mixtures of snow, rain, and sleet) may be several times the level expected for rain at the same rate. While it is considered unlikely that wet snowfall would limit a system designed with adequate margin for heavy warm-season rainfall, the available data are very inadequate, and this factor should be carefully considered in the design of future guidance systems if frequencies above 7 GHz are used.

Bending effects on the radio beam caused by low-level refractive gradients should not be a limiting factor in system design or operation _if_ glide slopes are kept above 2°. If it should be necessary to operate at angles of less than 1° the effects of refractive variations could become very important, and the refractive climates of areas where such operation is planned should be reviewed in detail.

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APPENDIX

Frequency of Occurrence of Various Gradients

Worldwide data on the frequency of occurrence of abnormal gradients are presented in several publications. The location and probability of ground-based superrefractive and subrefractive layers are discussed in the "World Atlas of Atmospheric Radio Refractivity" by Bean et al. (1966), and Cahoon and Riggs (1964) give maps of the heights and percentage of occurrence (if greater than 40 percent) of elevated layers caused by subsidence. These data have certain limitations, mostly due to the sparsity of observations in both space and time. The refractive data are based upon radiosonde observations (RAOB's); the percentages given in the cumulative distributions refer to the percentage of RAOB observations analyzed, and not to the percentage of total (annual) time. One month was selected to represent a 3-month "season"; thus, February, May, August, and November are the only months referred to in the discussion that follows.

Five-year cumulative distributions of the gradient observed in the ground-based 50-m layer are shown in figures A1 through A9 at locations near nine terminals: Seattle, Oakland (San Francisco), Long Beach (Los Angeles), Miami, Denver, Joliet (Chicago), Atlanta, New York, and Washington, D. C. Table A1 supplements these data by giving the gradient found at set percentage levels (corresponding to the bottom scale of the U. S. graphs) at various stations that are at or near major world airports. The percentage of occurrence of subrefractive and ducting gradients is also given.

The U. S. west coast stations of Seattle, Oakland, and Long Beach (figures A1 to A3) show a small percentage of occurrence of anamolous gradients (less than 15 percent of either subrefraction or

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ducting) because of the moderating effect of the ocean on the temperature distributions. This is particularly true of Seattle and Oakland, both located in large bays and both in the latitude of prevailing westerly winds. Ground-based gradient data at Seattle (0700 and 1900 LST RAOB's) reveal very little subrefraction (maximum of 1 percent in August). Gradient data were not available for September and October, but the normal weather conditions at these two stations indicate a seasonal peak of subrefraction associated with fog formation (moist ocean air being transported over a cooled land mass) could be expected near sunrise in September (extending through October if the major storm season were delayed). Seattle has a climate characterized by a winter maximum of cyclonic storm action and, therefore, a winter minimum of anomalous signal propagation. Precipitation is high and temperature range low because of the marine influence.

The refractivity climate of Great Britain (including London) and the coastal portions of South Central Europe are similar to the Washington and Oregon coasts, particularly in winter, because of similar latitude, upper atmospheric circulations, and nearby warm ocean currents. Even the coastal plains of France and Germany (including the cities of Paris and Berlin) show a strong marine influence, although the continental temperature influence increases with distance from the coast. Larger diurnal temperature differences at inland locations produce more nighttime temperature inversions and, therefore, more superrefraction.

Figures A2 and A3 show that both Oakland and Long Beach can expect a greater percentage of both subrefraction and superrefraction in February and November than in the warmer months. During fall, winter, and early spring, winds are light, and low surface temperature inversions are very common in the early morning, except during a few

periods of heavy rain. In the cooler months Long Beach not only has more subrefraction than Oakland but also has a larger incidence of dense fog. In fact, in November when Long Beach shows a 13 percent occurrence of subrefraction and Oakland 5 percent, the days of heavy fog at Los Angeles are twice those at San Francisco (USWB, 1967); the days are also doubled in October and December. Early morning subrefractive surface gradients usually are formed during periods when the onshore pressure gradient becomes weak (anticyclonic circulation to the north), permitting a fairly strong north to northeast downslope wind which dries the ground and the surface atmospheric layer. During periods of onshore wind flow, when temperatures are 10°C (50°F) or more, superrefractive gradients occur. (Note that Long Beach, with warmer temperatures, averages ducting gradients 13 percent of the time as compared to Oakland's incidence of 7 percent.

In the summer the upper air circulation changes, and the temperature inversion is much higher, especially at Oakland. Subsiding air from the eastern portion of the Pacific anticyclone typically forms an inversion layer that extends from about 600 m to 1200 m above sea level. Its horizontal extent is controlled by the California coastal terrain. The boundary between the surface marine layer and this inversion layer becomes the base of an elevated refractivity duct, which extends upward from 150 m to 300 m and can be as intense as 500 N-units/km. At the Oakland airport these ducts are present at 0700 and 1900 LST 50 percent of the time in August and 20 percent of the time in May, but the incidence in only 15 percent at 0100 LST and 8 percent at 1300 LST in both May and August. At Long Beach the percentage occurrence in August is 50 percent at 0700 and 60 percent at 1900 LST; in May the elevated ducting occurrence is 30 percent at 0700 and 40 percent at 1900, with November showing only 15 percent

at 0700 but increasing to 25 percent at 1900 LST. (Observations were not available at 0100 and 1300 LST at Long Beach.) The bases of those layers vary in height from 200 m to 900 m, but are slightly lower in the afternoons, and thicker and more intense in August than in the transitional months.

The significance of these elevated ducting layers to aircraft approach systems is two-fold. First, the layers in this particular region occur in the atmospheric layer within 1 km of the surface, so that an aircraft on an approach would normally pass in and out of the intense change in refractivity (which could result in a weakening or momentary loss of signal) on its approach (Dougherty, 1967). Second, wind speeds may vary rapidly through an inversion layer; usually there is a minimum of wind speed near the base of an inversion and above this the speed increases rapidly with height, reaching a peak in the upper half of the inversion layer. About half the time during August this produces a pronounced wind shear at about 700 m to 800 m in the San Francisco area (Miller, 1968).

The climate at Oakland and Long Beach is similar to that experienced in the vicinity of the Mediterranean Sea (particularly the southern and eastern parts). Winter surface refractivity is comparable, and low elevated ducting layers are found in both locations in the summer months. In August, for example, Rome, Italy, at 0100 LST has elevated ducts with bases averaging 600 m at least 5 percent of the time; Nicosia, Cyprus, at 2200 LST has bases averaging 200 m for 25 percent of the time, and at 1000 LST the bases near 350 m occurred 6 percent of the time; Port Lyautey, Morocco, at 0200 and 1400 LST has elevated layers with bases ranging from 200 m to 800 m during 49 percent to 53 percent of the observations.

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Other world airports that might have similar refractivity patterns in their corresponding seasons would be Perth, Australia; Santiago, Chile; Bet Dagan, Israel; Lisbon, Portugal; and Mazatlan, Mexico. However, the height of the inversion layer at most of these stations is greater than 1 km and, therefore, less important to approach system operation.

Miami, Florida (figure A4), has a definite wet and dry season, which resembles in many ways the coastal wet-dry tropical climate of Central America, parts of Brazil and India, northern Australia, and much of Southeast Asia. Surface refractivity gradients during the cooler dry season at Miami (November and February, as indicated by the graphs) appear to be fairly standard, but locations nearer the Equator (such as Balboa, C. Z.; see Table A1) experience more intense solar heating that produces a small percentage of Type A subrefractive gradients. In fact, the winter climate of a wet-dry tropical station compares with climates found in tropical desert and steppe areas, whereas the summer weather is comparable with that found in tropical rainy climates (especially if the locations are within 20° of the Equator). Miami, at 26°N, experiences some intense superrefractive gradients from 100 m to 400 m deep, mostly during the night and early morning in summer; however, the amount and intensity of surface ducting gradients at many tropical stations exceed that of Miami's warm season.

Tropical locations have great diurnal and interdiurnal variations in surface refractivity gradients, because, with temperatures above 20°C, a small change in humidity with height is critical to the refractivity gradient. Stations on the coasts of tropical inland seas or gulfs with highlands on the shore opposite the prevailing wind direction seem to show the most intense and persistent ducting because of the thermal effects between land and the enclosed sea. Another major area of

ducting is found in the monsoon regions when the temperatures are warm and humidities high (i.e., Calcutta in May and November in Table A1) in the weeks or month immediately before or after the peak of convective storms. Nocturnal ducting also occurs in tropical coastal locations where onshore surface winds create a humid maritime layer which pushes under the dry anticyclonic circulation of the large subtropical high (e.g., see Dakar in Table A1). Onshore winds from a large lake may create the same effect at an interior station. Seasons in the tropics are determined more by precipitation, humidity, and the availability of water than by temperature; therefore, the prevailing winds, the altitude of a station, and the terrain are very important in determining the surface refractive gradient. The result is that superrefractive layers may occur one evening and Type B subrefractive layers the following evening. Likewise, subrefraction may characterize the surface gradient at a location one morning and superrefraction the next.

The refractivity found at Denver (figure A5) would be fairly typical of the gradients that could be expected in any arid plateau region on the lee side of a major mountain chain (e.g., Salt Lake City, Utah, and Tehran, Iran). During the spring and summer most of the subrefraction is Type A, caused by strong daytime surface heating; in such conditions the ceiling and visibility would probably be unrestricted. All months show some superrefraction associated with nighttime inversions, but the percentage of occurrence is much smaller at high altitude airports in dry climates than at low altitude airports in very moist (and warm) climates. Joliet (figure A6) in summer and Atlanta (figure A7) in spring, summer, and autumn fit this last category. Plains area airports (especially those in a valley with downslope air drainage) may have a significant amount of temperature inversions. If the ground surface is moist, superrefractive gradients are formed,

with or without fog. Some major Plains airports where these conditions are found part of the time are Omaha, Minneapolis, Kansas City, and Cleveland.

The Middle Atlantic and Northeastern Coastal states of the U. S., including New York and Washington, D. C. (figures A8 and A9), have almost as much subrefraction in surface atmospheric layers as superrefraction. The majority of both types of refractive layers occur at night or early morning with temperature inversions. Most of the subrefraction can be attributed to advection of moist, warm air brought in at upper levels during certain air mass movements; in spring and autumn this subrefraction is usually accompanied by a shallow fog layer. The temperature inversions with superrefraction are usually deeper and more intense. When the surface humidity is extremely high, and the advected upper layer is much warmer and drier, fog may accompany the superrefraction. Anomalous propagation (caused by abnormal refraction) can be expected more often in summer than in winter in these areas, because the more intense circulations of winter tend to mix the lower atmosphere to greater depths and thus reduce the possibility of strong refractive gradients.

Intense surface inversions at any of these airports may also produce the same type of wind shear found in some elevated inversions. In a study of the Washington, D. C., area, Roberts (1969) found that critical (to aircraft landings) vertical shears exceeding 10 knots/100 ft may be expected in the first 100 ft above the ground whenever the temperature gradient increase exceeds $4^{\circ}C/100$ ft.

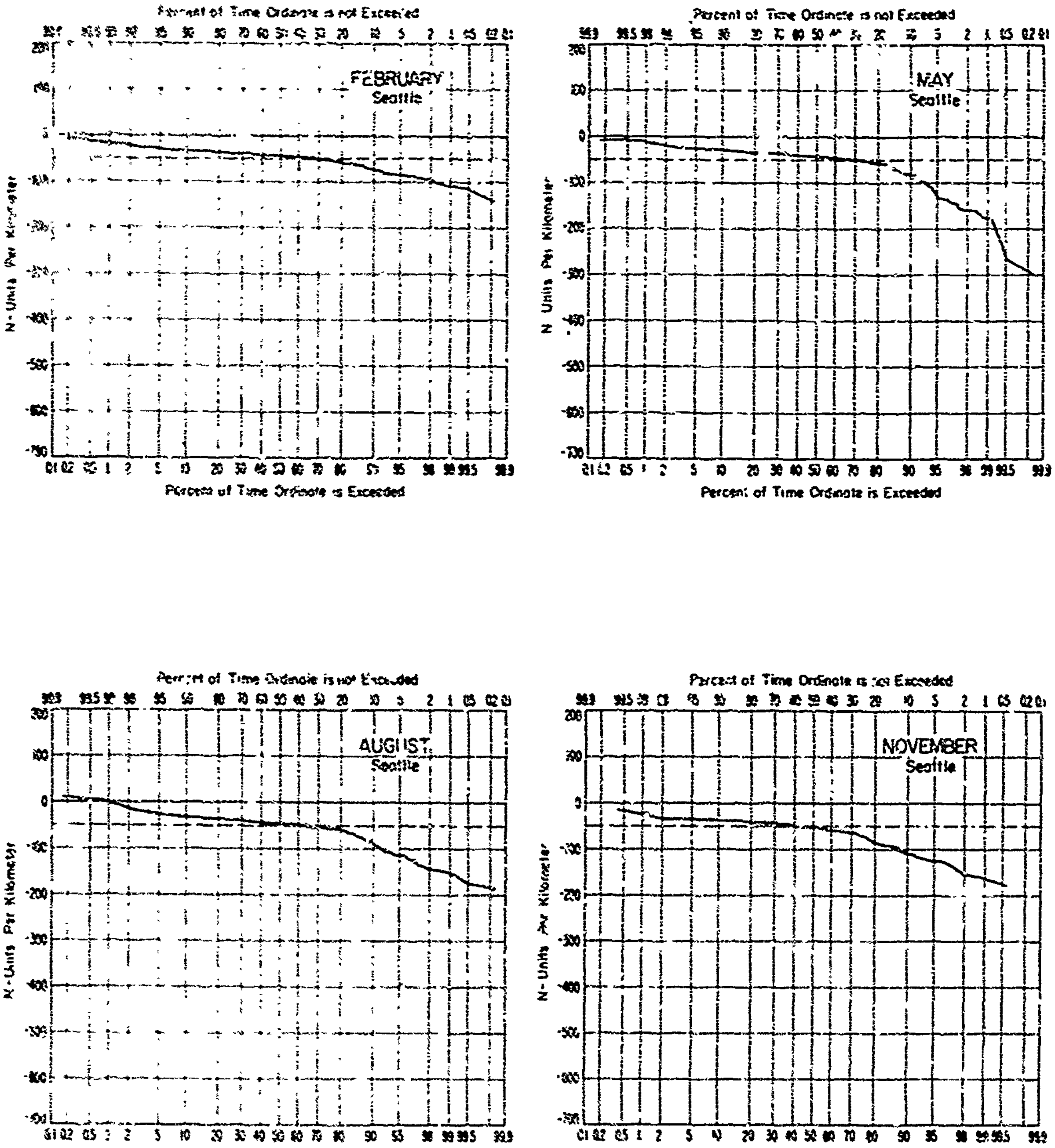

Figure A1. Cumulative probability distribution of dN/dh for a ground-based 50-m layer (Seattle, Wash.).

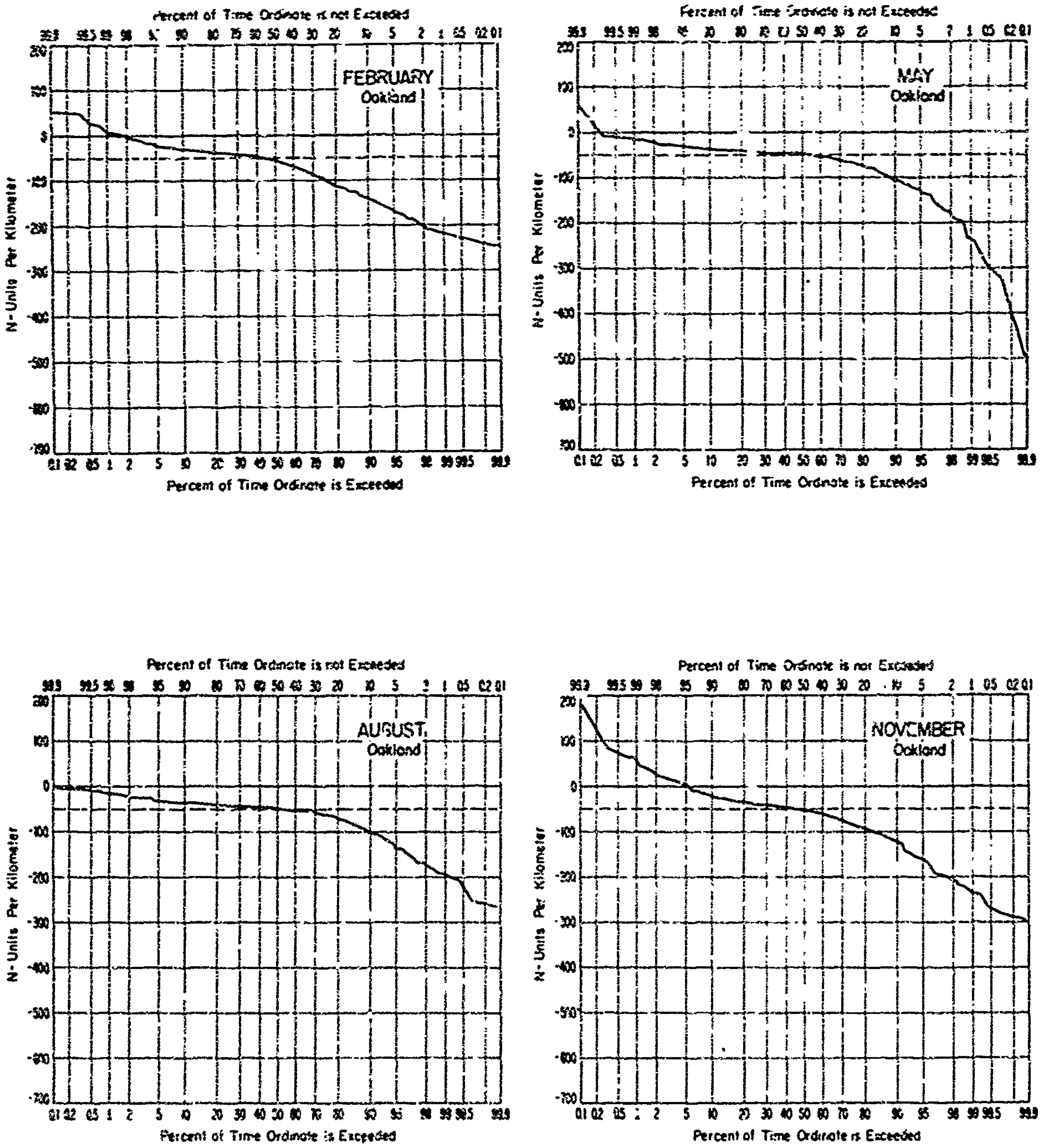

Figure A2. Cumulative probability distribution of dN/dh for a ground-based 50-m layer (Oakland, Calif.).

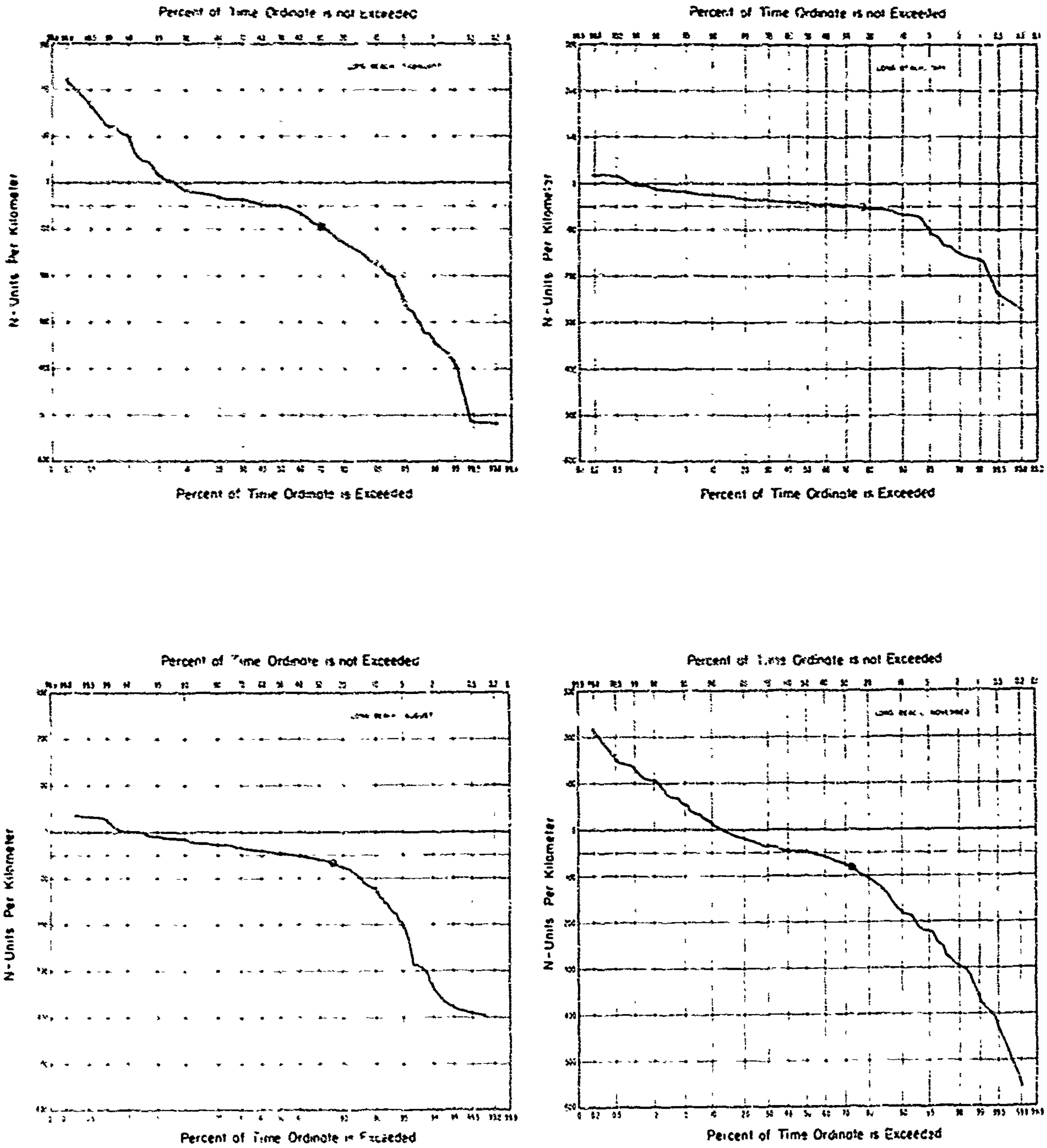

Figure A3. Cumulative probability distribution of dN/dh for a ground-based 50-m layer (Long Beach, Calif.).

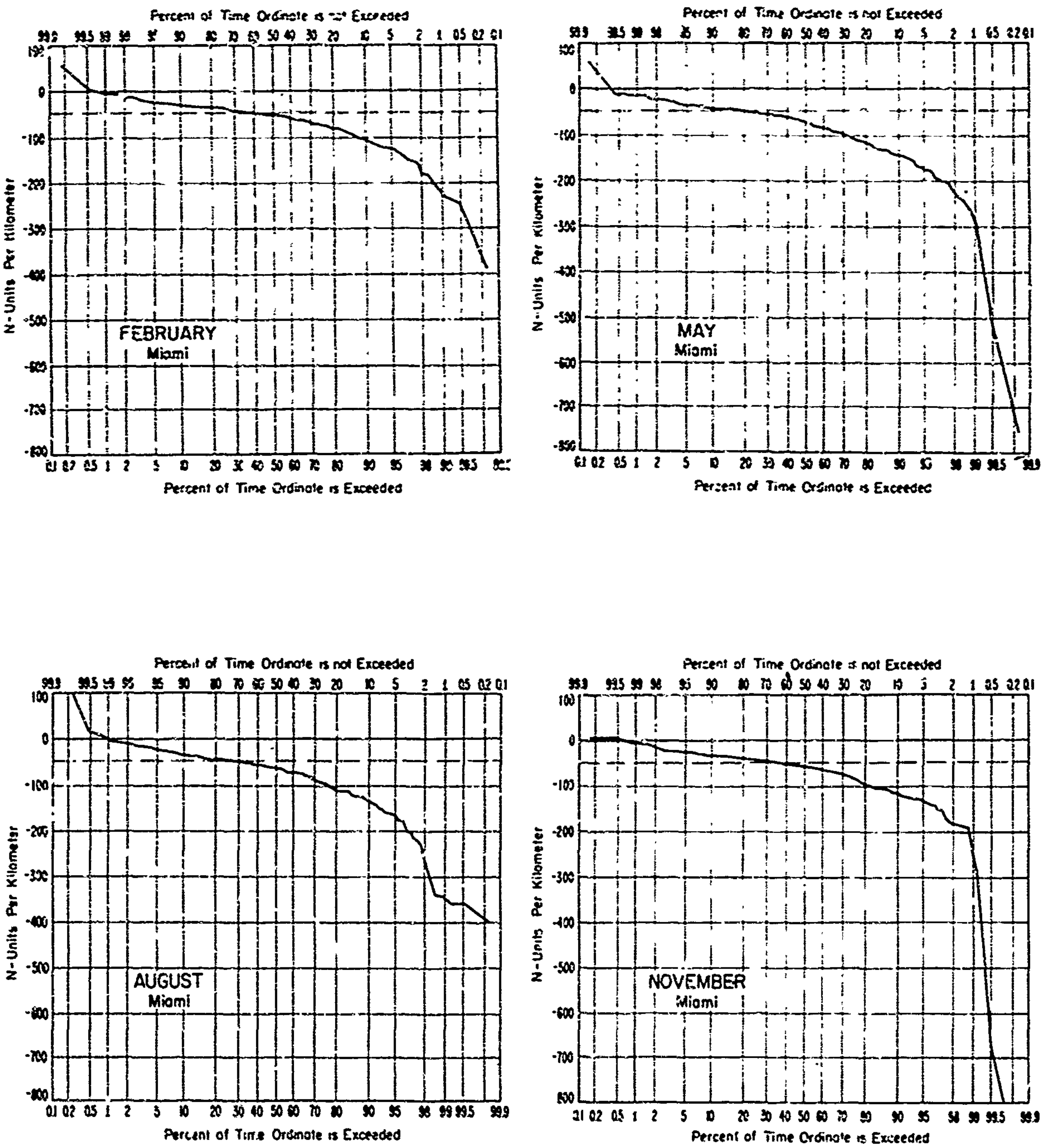

Figure A4. Cumulative probability distribution of dN/dh for a ground-based 50-m layer (Miami, Fla.).

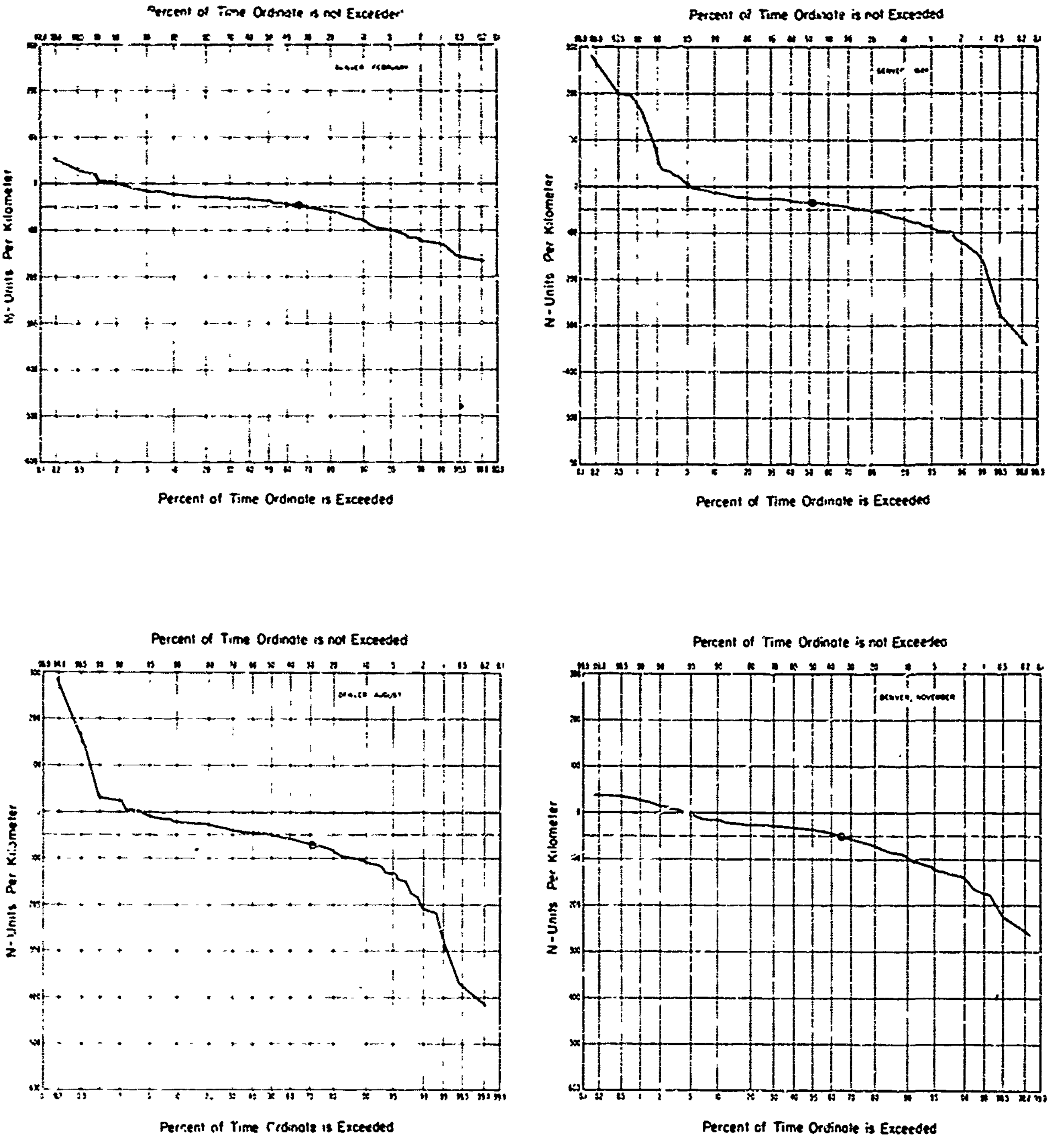

Figure A5. Cumulative probability distribution of dN/dh for a ground-based 50-m layer (Denver, Colo.).

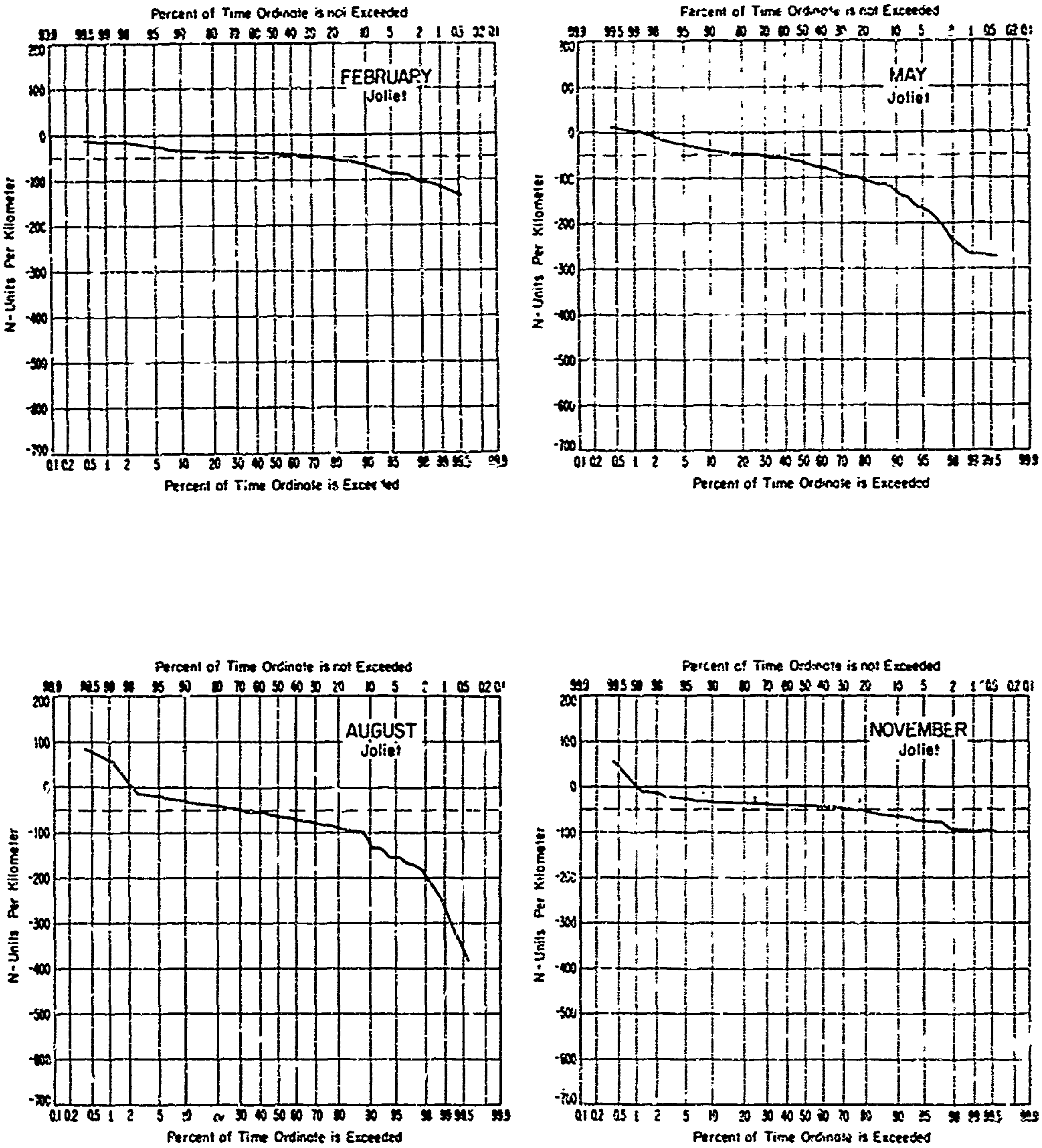

Figure A6. Cumulative probability distribution of dN/dh for a ground-based 50-m layer (Joliet, Ill.).

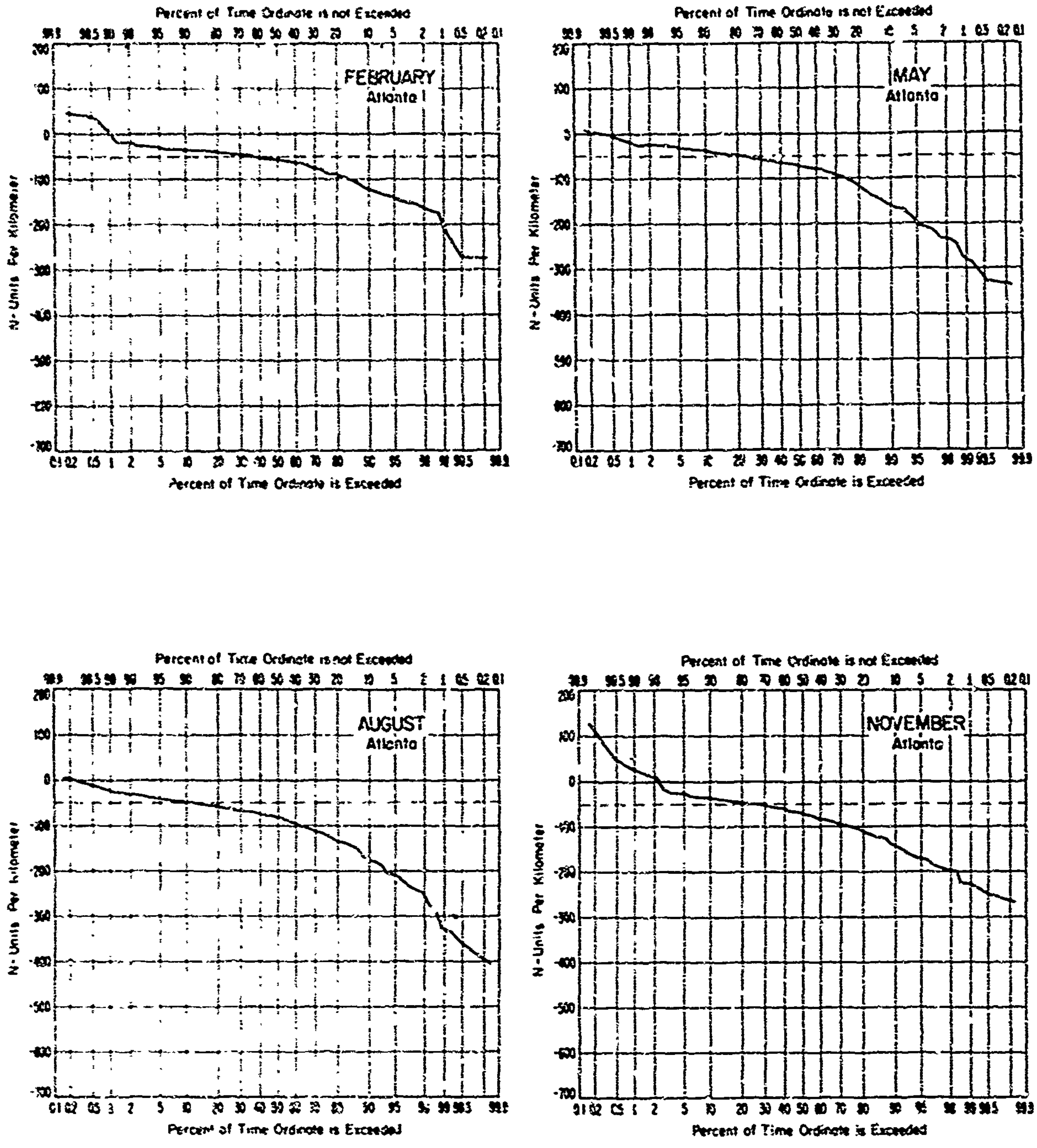

Figure A7. Cumulative probability distribution of dN/dh for a ground-based 50-m layer (Atlanta, Ga.).

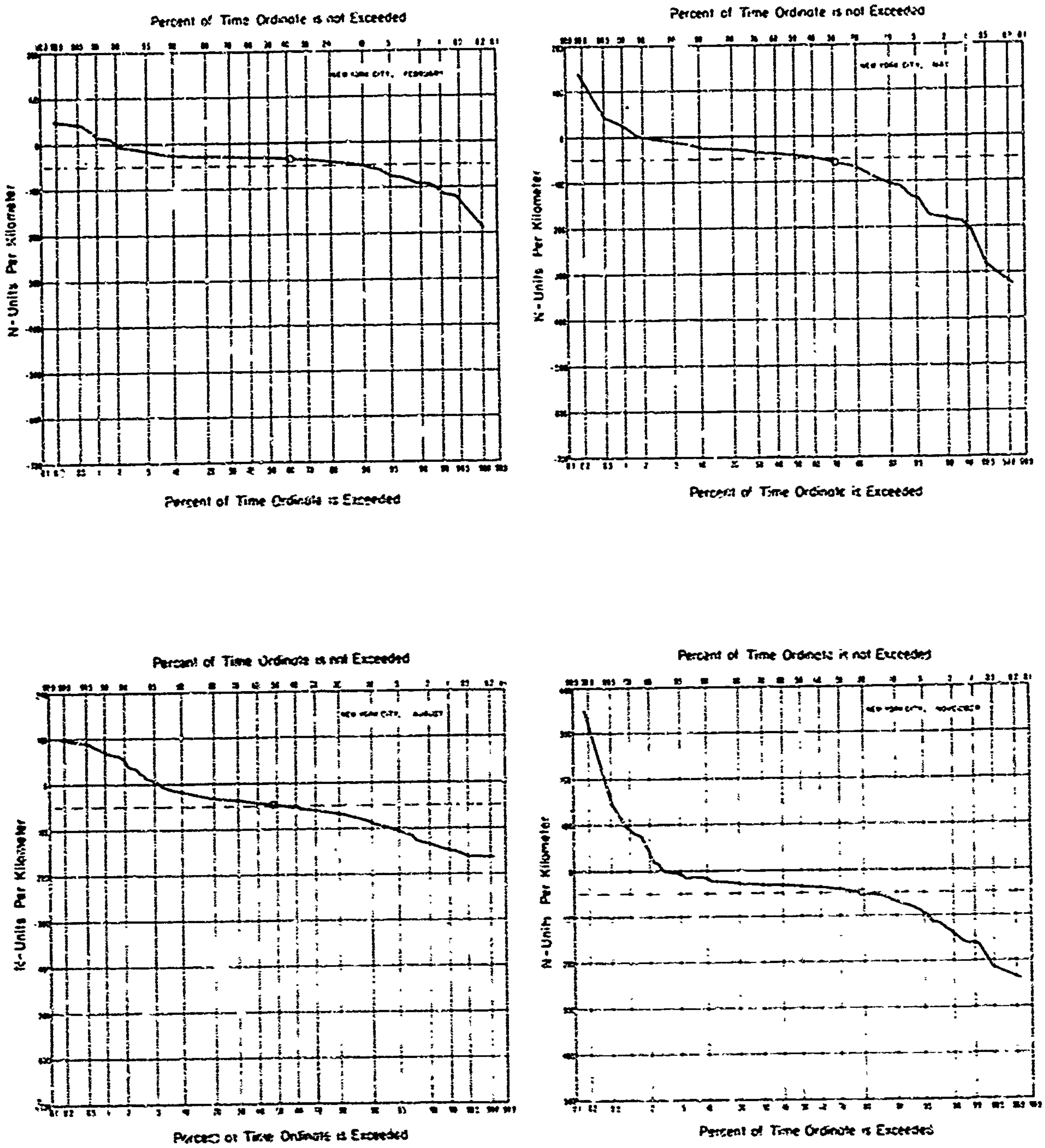

Figure A8. Cumulative probability distribution of dN/dh for a ground-based 50-m layer (New York, N.Y.).

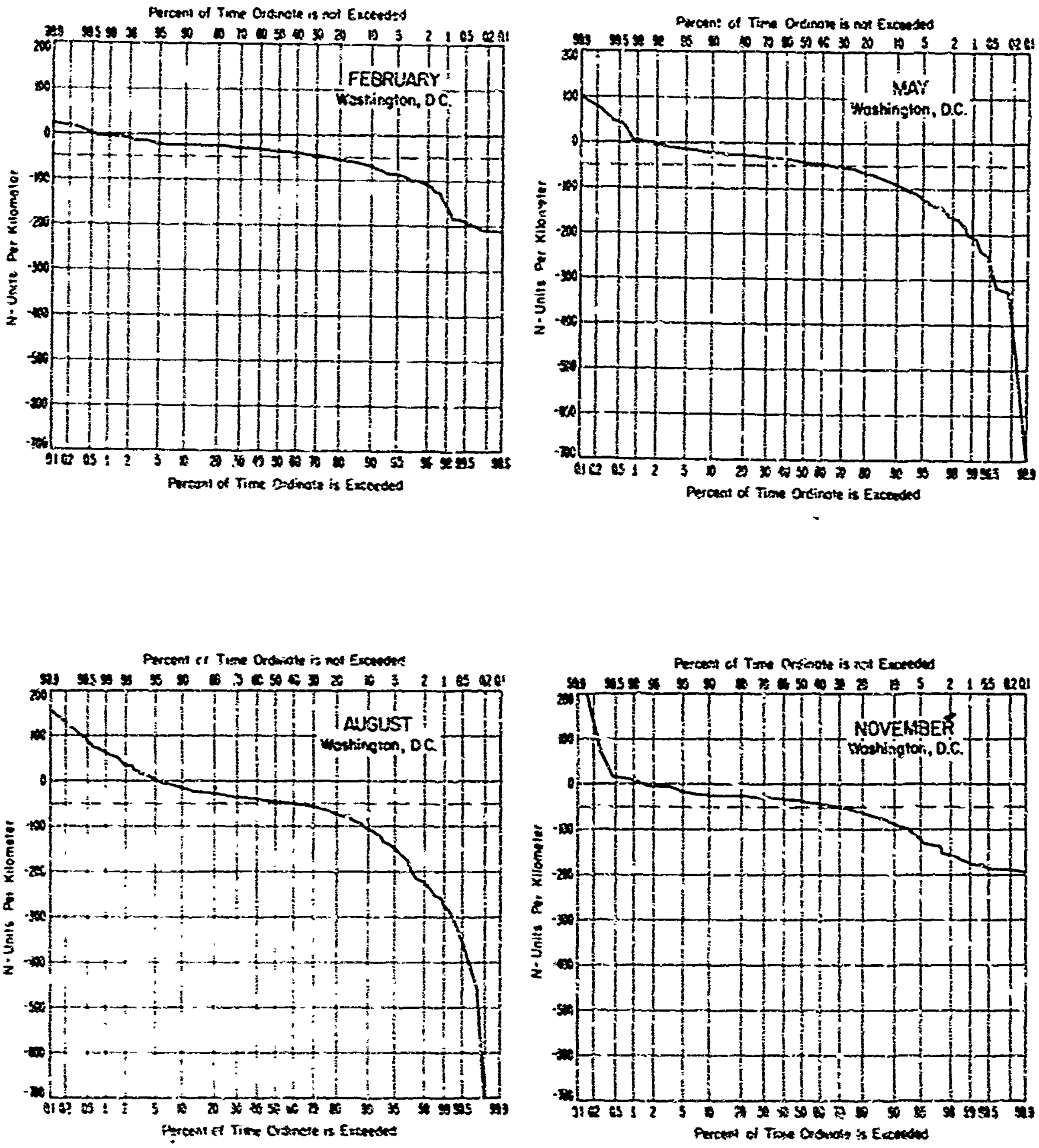

Figure A9. Cumulative probability distribution of dN/dh for a ground-based 50-m layer (Washington, D.C.).

Table A1. Ground-Based Gradients (Surface to 50 m)

Station	in N-Units / km					Percentage Occurrence	
	1%	5%	50%	95%	99%	Subrefract.	Ducting
Aden, Arabia							
February	200	56	-55	-160	-350	13%	5%
May	368	98	-68	-283	-542	19	21
August	201	85	-58	-235	-397	11	15
November	253	56	-39	-138	-556	23	4
Anchorage, Alaska							
February	-17	-28	-42	-127	-168	0	2
May	0	-24	-42	-95	-165	1	1
August	39	8	-46	-109	-164	7	2
November	10	-11	-44	-97	-115	2	<1
Argentia, Newfoundland							
February	1	-22	-32	-52	-109	1	1
May	20	-8	-37	-74	-111	4	<1
August	0	-18	-47	-144	-232	1	4
November	36	-13	-37	-86	-343	3	2
Balboa, Canal Zone							
February	42	-14	-63	-165	-446	3	6
May	5	-25	-63	-140	-197	2	3
August	6	-32	-66	-164	-248	1	6
November	69	2	-67	-222	-361	5	12
Bitburg, Germany (similar to Berlin)							
February	-4	-25	-37	-49	-57	0	0
May	45	-20	-34	-67	-210	2	1
August	58	17	-37	-55	-96	8	1
November	9	-6	-32	-47	-56	2	0
Bordeaux, France (similar to Paris, but more humid)							
February	16	-22	-55	-157	-242	1	5
May	27	-18	-73	-264	-362	4	13
August	33	-23	-75	-226	-469	2	11
November	-15	-27	-63	-162	-251	0	6
Calcutta, India							
February	111	1	-108	-297	-553	7	6
May	91	-13	-68	-223	-443	3	15
August	26	-26	-68	-192	-235	2	8
November	51	-29	-127	-307	-454	2	33
Dakar, Senegal							
February	197	30	-207	-708	1321	8	62
May	241	97.	-118	-425	-674	15	35
August	321	100	-115	-345	-534	13	51
November	235	42	-177	-701	-1086	10	54

Table A1. *Ground-Based Gradients (Surface to 50 m)* — Continued

Station	in N-Units/km					Percentage Occurrence	
	1%	5%	50%	95%	99%	Subrefract.	Ducting
Ezeiza (Buenos Aires), Argentina							
February	366	46	-38	-203	-353	19	6
May	94	57	-44	-108	-129	11	0
August	29	24	-47	-140	-193	5	3
November	71	44	-28	-145	-357	22	2
Hilo, Hawaii							
February	50	13	-53	-135	-187	7	3
May	8	-22	-63	-146	-183	2	3
August	46	2	-72	-189	-270	5	9
November	68	20	-61	-142	-186	7	3
Moscow, U.S.S.R.							
February	-24	-30	-38	-56	-73	<1	0
May	11	-10	-38	-71	-92	3	0
August	12	-2	-44	-73	-96	3	0
November	-18	-28	-38	-53	-[illegible]	0	0
Perth, Australia							
February	70	25	-29	-69	-130	13	0
May	78	26	-39	-114	-281	10	2
August	166	1	-43	-94	-127	5	<1
November	203	1	-35	-91	-167	5	1
Recife, Brazil							
February	-2	-27	-62	-123	-250	<1	3
May	-26	-39	-62	-164	-419	0	6
August	-23	-35	-58	-107	-145	<1	0
November	41	-21	-59	-170	-273	1	5
San Juan, Puerto Rico							
February	-15	-35	-65	-145	-191	0	4
May	-13	-36	-74	-175	-233	<1	8
August	-23	-43	-73	-177	-223	<1	8
November	1	-34	-71	-177	-241	1	8
Singapore							
February	10	-31	-73	-156	-191	<1	5
May	110	2	-82	-173	-242	5	7
August	10	-18	-72	-157	-207	<1	5
November	-21	-28	-79	-138	-239	1	4
Tateno (Tokyo), Japan							
February	-2	-20	-49	-96	-109	<1	0
May	67	-19	-52	-126	-143	4	<1
August	40	-5	-57	-131	-181	2	2
November	-5	-16	-49	-106	-144	<1	0

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15. Supplementary Notes

16. Abstract

The operation of approach and landing systems can be affected by precipitation, turbulence, atmospheric refraction, and other atmospheric phenomena, yet the demands on the system are highest under the most adverse conditions. Information is presented on the probable magnitude of the various weather-related effects, considering differences in radio frequencies, geographical location, and climate; rain attenuation is the most critical limiting factor at frequencies above about 7.5 GHz.

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